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Phosphorus in runoff water as affected by amount added to soil and rainfall energy

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ABSTRACT

The amounts of phosphorus (P) in runoff water as affected by the amount of P added to soil and reducing rainfall energy were investigated using a rainfall simulator under laboratory conditions. The objectives of this study were to determine 1) how soil available P levels are increased with added P for those Iowa soils (Nicollet, Marshall, and Fayette), 2) how orthophosphate-P (PO_4-P) and total-P concentrations in surface runoff are affected by the added P for these soils, 3) how the hydrology and P concentrations and losses are affected with the Nicollet soil when rainfall energy is dissipated by a screen, and 4) how added P affects P concentrations and losses for water drainage through a thin layer of soil.

The soils used in this project were sieved to obtain a reasonable degree of fines without appreciably destroying the original soil structure. Soils, allowed to partially air dry in the laboratory, were sifted through a 2.5 mm sieve and then thoroughly mixed. A plastic runoff box, 83.5 cm long by 42.3 cm wide, resulting in a 3490 cm^2 rainfall collection area, was used. The treatments of 0, 50, 125, 300, and 600 ppm (on a dry weight of soil basis) of added monobasic ammonium phosphate (MAP) were dissolved in water and sprayed on soil as it tumbled in a mixer. The soil was incubated in a plastic box for a period of 30 d to allow the MAP to interact with the soil, before using with the rainfall simulator. P added to these soils increased P concentrations in runoff and subsurface drainage. The Nicollet soil, contained more sand (38%), had more P in subsurface drainage compared to Marshall soil which had more clay (27.6%) and was more impermeable to water penetration. The percent the clay for Fayette soil was (26.0%). The effect of the screen cover was to alleviate the

impact of the rainfall energy on bare soil which reduced the detachment of soils particles and facilitated water penetration though soil layer for subsurface collection proposes.

CHAPTER 1. INTRODUCTION

The oldest activity that humans have preserved developed, and continued to update is the practice of agriculture. Agriculture is the main source of our food production; however, it is also the principal source of nonpoint source pollution of soil, water, and air resources. Management practices in agriculture sometimes involve the application of either manure or fertilizer in excess of crop needs, which consequently can result in serious economic, environmental, and social problems because of off-site transport of nutrients.

In most cases, it is fortunate that P is not as easily lost to water as nitrate-nitrogen (NO_3-N) because, as with NO_3-N, increasing levels can cause an excessive growth of algae and eutrophication. The concern with P is that only a small increase in loss can cause problems. Therefore, care is needed to prevent even small P losses especially from light sandy soils that do not retain P as well as clay soils. Also, if heavy rain falls just after P fertilizer or manure has been applied, there may not be enough time for the P to bond properly to the soil. Heavy rain along with the excessive use of organic manures may result in an excessive loss of dissolved P. Dissolved P is released into surface runoff water from the thin layer of surface soil that interacts with rainfall and runoff.

In addition to protecting water quality and the environment, even though there are no health concerns directly associated with P in drinking waters, it is necessary for individual farm owners and operators to understand the sources of P pollution. In this new era of environmental concerns with manure, management plans should be periodically reviewed and possibly revised in cases where a facility increases in size or changes its method of fertilizer or manure management, or if other operating conditions change. Since most water

quality problems have a land use origin, the understanding of land use practices will assist in addressing water quality concerns.

CHAPTER 2. LITERATURE REVIEW

Mixing Zone Affected by the Rainfall Energy

Ahuja et al. (1981) found by using ^{32}P as a tracer at several soil depths that the degree of interaction between soil and rainfall-runoff was dominant at the surface and decreased very rapidly with depth. He proposed that the effective depth of interaction (EDI) be defined as the thickness of surface soil in which the influence of the interaction is proportional to the total contact area. The kinetic energy relations of natural rainfall were used to study the relative effects of the factors involved. The scope of their study was concerned strictly with the release of soluble P to runoff water. They found that it was important to take into consideration the solution P component, even for the soil types with considerable P-fixation capacity.

There are two physical processes that take place during the development and maintenance of the EDI during a runoff event. The raindrop impact on the soil surface initiating a turbulent mixing of water in a thin surface zone, and the energy of runoff as it moves down slope. Ahuja et al. (1981) hypothesized that the action of the raindrop influence increases with increasing rainfall intensity. The initial formation of the EDI will be a function of the degree of soil aggregation. Well aggregated soil gives a stronger stability to soil structure than poorly aggregated soil (Sharpley, 1985). A similar study to Ahuja's of $CaSO_4$ movement from soil into surface runoff found that the kinetic energy of rainfall and the soil slope are important influential factors to this process (Ingram and Woolhiser, 1980). P, similar to less mobile fertilizers and pesticides, is released from a thin surface layer of soil surface that interacts with rainfall and runoff during the overland flow transport process. The

conventional mixing zone theory assumes that there exists a correlation between the thickness of the interaction zone, rainfall intensity, and slope (Sharpley, 1985). The mixing concept has been widely accepted and used to predict chemical losses in surface runoff (Donigian et al., 1977; Frere et al., 1980; and Ahuja et al., 1981).

Measurement of Phosphorus Loss in the Soil

It has been recognized for more than a century that after P has been added to a soil, only a relatively small fraction of added P is recovered in crops grown on that soil. Researchers have been involved in this issue because it is concerned with the efficiency of fertilizer use and the impact of rainfall in the economy of crop production (Koswara, 1966). Many studies have focused on different approaches to understand the processes involved in the P uptake of crops. The obtained knowledge has been used in predicting optimum rates, times, and methods of fertilizer P applications. In predicting the relative effectiveness of fertilizer P applications as a means of increasing crop yields, it is necessary to consider the relative availability of both the soil P and the added P.

Koswara and Hanway (1969) strongly affirmed the reliable predictions of the increase in crop yields that may be expected from applications of fertilizer P on any particular soil depending upon estimates of the relative availability of both the soil P and the added P. Chemical analysis has been used with success to measure the relative availability of soil P to plants. Ozus and Isobe (1969) found that the Bray method was an excellent index of determining the availability of soil P in Iowa soils. However, it is still vague concerning the relative availability of added P to different Iowa soils. Ozus and Isobe (1966) showed that the availability of P added might be different in different soils. Uniform P field experiments were conducted in 1951 and 1952 using ^{32}P labeled fertilizers in a cooperative study among

universities in many states and the U.S. Department of Agriculture (1953). Soil samples collected during the experiments were used in greenhouse and laboratory studies. Extrapolation of yield-of-P (i.e., the uptake of added P) curves from the greenhouse data to the point of intersection with the X-axis gave an estimate of the available P ("a" value), which approximated the "A" value obtained by using ^{32} P labeled fertilizer. The slope of the yield-of-P curves was influenced to a degree by the P-fixation process, as indicated by correlations with anion exchange capacities and with cation exchange capacity-anion exchange capacity ratios.

These correlations accounted for a very small fraction of the total variation, however, indicating either that the slopes of the yield-of-P curves were not appreciably affected by P fixation, or that the exchange capacity methods did not adequately reflect the influence by P fixation on P absorption by the plants. The U.S. Department of Agriculture (1953) reported that the recovery of added P from samples of the 28 soils by millet grown in the greenhouse for 5 weeks varied from 9 to 22%. Percentage recovery of added P decreased slightly as the rate of added P increased, but was not consistently related to the level of P availability in the soils, soil pH, soil texture, organic matter content, or other measured physical and chemical properties of the soils. The "A" values and "a" values generally increased as the rate of added P increased, but the results from the different rates of added P ranked the soils in essentially the same order. Within the group of 28 Iowa soils, the "a" values were generally similar to the "A" values, but there were a few marked exceptions in which the amount of soil P taken up by the plants was either increased or decreased as a result of the P additions (Ulgen et al., 1962)

Alberta Agriculture (1995) assumed that all of the manure P applied to soil would eventually be available for plant uptake and chose application rates that balanced total P inputs with total P removal in the crop. Manure applications of 30 - 60 Mg/ha provided five to six times more P than was recommended for barley production. King et al. (1990) after 11 years of an annual application using swine lagoon liquid found that the levels of available P increased to a depth of 75 cm, but they predicted further downward migration of P would be slow due to increasing clay content and decreasing pH below 75 cm. Available P levels to a depth of 60 cm in loamy and clay soils from Alabama were more than six times greater in soils amended annually with poultry litter for 15 to 28 years than for nonamended soils (Kingery et al., 1994). Lutwick and Graveland (1978) found the P absorption capacity was related to clay content, cation exchange capacity, and ammonium acetate extractable calcium (Ca) and magnesium (Mg) in orthic Brown and orthric Dark Brown chernozenic soils from southern Alberta. The P absorption capacity of silty clay and silty clay loam soils ranged from 236 to 950 mg P/ kg soil for sampling depths from 0 to 180 cm.

Parfitt (1978) found that the reduction in the quantities of exchangeable Ca after repeated application of feedlot manure and irrigation, or colloid mediated transport of P due to increased soil dispersion with increasing sodium (Na) saturation, could partially explain the apparent movement of P in irrigated soils. James et al. (1996) found that calcareous soil in Utah had considerable capacity to hold P from turkey manure. Chemical and biological methods represent the two main groups of procedures that are most commonly used for determining a suitable index for P availability in soils. Plants or microorganisms are used as determining factors of extracting P from soil. The interpretation of those methods are made by correlative observation with crop response to P when grown on similar soils. Most

researchers have used plant response as a good indicator of added P as a good factor to be used to evaluate the availability or the effectiveness of applied P, and as a relative measure of a soil's capacity to fix P. Scarseth (1932) used a greenhouse experiment to determine the effect of time of an application on the effectiveness of applied P. The author used soybean plants that were grown for 48 days on the test soils before being harvested. Different rates of super phosphate were mixed with the test soils at 180, 90, and 30 days before planting, and at the time of planting. He found that an addition of 1130 kg/ha of super phosphate 180 days before planting produced the same response as an application of 280 kg/ha at the time of planting.

It is generally known that only a small fraction of added P can be recovered in crop plants grown on soils after P application. Much research has focused on that particular area to assess the importance of added P in soils and to clarify the mechanism that constitutes the key element involved. Soil reaction, soil texture, time and rate of P addition, temperature, and organic matter content are generally considered to be involved. Hirman et al. (1962) conducted an experiment of the effect of soil temperature and moisture on the solubility of added monocalcium phosphate in a calcareous soil of Saskatchewan. They found that water soluble P in the reaction zone increased with a decrease in temperature or an increase in moisture tension. The highest solubility was obtained at 6.0 bar moisture tension and at a temperature of 5^0 C. Kosware (1966) focused on the laboratory or greenhouse method, which deals with the determination of the availability of added P. He found that the availability of added P in a given soil is inversely correlated to its P fixing capacity and suggested that some of those influential factors concerning the fixation of phosphate must be reviewed.

Thorne (1964) added super phosphate to surface and subsoil samples of Tama, Fayette, Carrington, Webster, and Marshall silt loam soils from Iowa for laboratory and greenhouse studies. In the greenhouse, super phosphate, at the rate of 448 kg/ha (equivalent to 17.5 ppm P) was mixed with the soil 3 mon before planting. Tomato plants were grown for 3 weeks before being harvested. Fixation of P by the soil, as indicated by the response of the tomato plants, was less than that indicated by extraction in the laboratory with 0.02 N H_2SO_4 and a 1:200 soil to solution ratio. He found a greater amount of fixation was obtained by the chemical method than by crop response method. He realized that an addition of super phosphate at the time of planting resulted in larger crop responses than did additions of the same amounts 3 mon before planting.

Moore et al. (1957) found that recovery of added P by oat plants from five Wisconsin soils varied from 51 to 72%. Percentage recovery decreased slightly as the rate of added P increased from 0 to 589 ppm P. Smith (1961) found that current P applications resulted in larger increases in plant yield and P uptake by the plants than did applications made 1 or 2 years previously. The previous P applications averaged 56, 72, and 70% as effective as current P applications for the Floyd, Edina, and Ida soils, respectively. Results of another greenhouse experiment, in which soil samples from other Iowa soils were used, indicated that P applications made 1 or 2 years previously were 40 to 65% as effective as a current application. Eik et al. (1957) conducted a greenhouse experiment by using soil samples collected in 1955 from the field plots established by Smith in 1953 and 1954. Sorghum was grown on the soil samples without further P fertilization and on soil samples from the unfertilized field plots after treatments with super phosphate equivalent to those that had been applied in the field. Eik et al. (1957) found that the recovery of fertilizer P by the

sorghum plants was 45%, 46%, and 38% of the 1957 applications and 30%, 36%, and 24% of the 1953-54 applications for the Floyd, Edina, and Ida soils, respectively. Ulgen (1962) found that the relative effectiveness of residual P from the fertilizer applications made 7 to 9 years, previously compared with that of a current application, were 17.0% in the Edina soil and 22.6% in the Floyd soil when P fertilizer equivalent to 134 kg/ha of P_2O_5 had been applied. The relative effectiveness increased as the rate of P fertilizer application increased.

Environmental Concerns About Phosphorus Losses From Agriculture

Agricultural activities can cause water quality problems that damage aquatic habitat and stream channels. However, the agricultural impact on surface water and groundwater can be minimized by properly managing activities that cause pollution. When animals repeatedly graze directly on erodible stream banks, bank structures may become weakened causing soil to move directly into the stream. Excessive grazing on riparian vegetation reduces the ability of the vegetation to protect stream banks and to trap sediments. Nutrient inputs from grazing lands to surface water come mainly in the form of N and P from manure and decaying vegetation (Carpenter et al., 1994). Schepers and Francis (1982) found increases in soil nutrients in a cow-calf pasture in Nebraska. Nutrient levels there were correlated primarily with grazing density. For any grazing management measure to work, it must be tailored to fit the needs of the vegetation, terrain, class or kind of livestock, and particular operation involved.

N and P are the two major nutrients lost from agricultural land that can degrade water quality. All plants require nutrients for growth. In aquatic environments, nutrient availability usually limits plant growth. N and P generally are present at background or natural levels below 0.3 and 0.01 mg/L, respectively (EPA, 2000a). When P is introduced

into a body of fresh water causing higher P concentrations, aquatic plant productivity may increase dramatically. This process, referred to as eutrophication, may adversely affect the suitability of a given body of freshwater for other uses such as swimming, fishing, boating, etc. Eutrophication is a natural process whereby a lake or other body of water evolves from a low productivity/low nutrient concentration state to a high productivity/high nutrient concentration state. Adequate P or excessive availability for plants stimulates early growth and hastens maturity. Although P is indispensable for plant growth, mismanagement of P can create a threat to the environment and water quality. The concentration of P can be sufficiently low in freshwater resources such that algae growth is limited. When lakes and rivers are polluted with excess P, there will be an increase in the rate of the eutrophication process.

P occurs naturally in soil, mainly in mineral forms; however, it can also be found in organic matter. P can be found in the soil in dissolved, colloidal, or particulate forms. Although the P content of most soils in their natural condition is low (0.01 to 0.2% by weight), soil test results show that the available P content of most cropped soils in the northeast U.S. has climbed to the high or very high range (Sims, 1992). Applying manure and P fertilizers increases the level of available P in the soil to promote plant growth, but many soils now contain higher P levels than plants need (Sharpley et al., 1994). Manures are normally applied at rates to meet crop N needs, yet the ratio of N to P in most manures results in over-application of P (Sharpley et al., 1996). When rainfall, snowmelt, or irrigation water runs over land or through the ground, it picks up P and deposits it into rivers, lakes, and coastal waters, or introduces the P into groundwater. Imagine the path taken by a single raindrop from the time the raindrop hits the ground to when it reaches a river, groundwater,

or the ocean. Any P the raindrop picks up on its journey can become part of the eutrophication problem. P is transported in dissolved (DP) and particulate (PP) forms. Most often P is sediment-attached. However, either form can contribute to eutrophication. Particulate P includes P sorbed by soil particles and in organic matter eroded during flow events, and usually constitutes the major portion of P transported from cultivated land–about 60 to 90%. Runoff from grass or forested land carries little sediment, and is therefore generally dominated by DP. While DP is, for the most part, immediately available for biological uptake, PP availability can vary from 10 to 90%, depending on the nature of the eroding soil. Together, DP and bioavailable PP constitute bioavailable-P (BAP) or P available for assimilation by aquatic life (EPA 2000).

During the transport of P from the edge of a field down stream to a receiving water body, DP and PP fractions continuously change as a result of in-stream processes. These processes include uptake of DP by aquatic life, transformations between PP, and DP caused by changes in stream equilibrium concentrations, deposition of suspended PP and re-suspension of streambed or stream-bank PP. The direction and extent of these P transformations during transport depend on the time of year, the relative amounts of P entering from different sources, and, in particular, the rate of flow (Sharpley and Rekolainen, 1997). According to Sharpley and Rekolainen (1997), the amount of P moving with runoff from uncultivated land is known as background loading. Little information is available on background losses of P from agriculture except that this background loading is not easy to reduce. In order to reduce the impact of P escaping to surface waters if economically feasible, farmers must reduce the amount of P fertilizer applied. Based on different studies and observations, it is not easy to quantify any increase in P loss following different

cultivation operations. Some different studies done in the U.S. summarized by the U.S. department of Agricultural (1953) show that P loss in runoff increases as the portion of the catchments under protected land diminishes and agriculture use increases. The amount of P that escapes from covered land tends to be the same amount of that found in subsurface drainage flow from cultivated land (Ryden et al., 1973). Taylor et al. (1971) found that covered catchments hold P. They realized that P input from rainfall usually exceeded outputs in stream flows.

Agricultural Phosphorus Balance

Whalen and Chi-Change (2001) reported that manure application guidelines in Alberta are based on crop N demands. Cattle feedlot manure has a lower N to P ratio (4:1 to 8:1) than crop needs (6:1 to 8:1), and manure applications based on crop N needs tend to supply P in excess of crops P needs. The authors realized that there was an apparent imbalance between P applied in manure and P recovered in soil and crop pools, which suggests that losses of P through surface runoff or erosion in non-irrigated plots were negligible. During their study, Walen and Chi-Change found added P concentrations at the depths up to 150 cm have increases P movement through the soil profile, which can be expected in some sites due to the presence of calcareous clay loam and the considerable capacity to absorb P applied in excess of plant P demands.

Aarts et al. (1993) found that excretion rates of P indicate a poor retention of P in animal feed, with values of 70 – 80% measured for dairy cows, sheep (Maynes and Iserhan, 1992), and feeder pigs (Archer, 1985), and 87% for poultry (Iserman, 1990). Without a doubt, agricultural systems which include confined animal feeding operations (CAFOs) can determine the overall efficiency of P recycling in agriculture and thereby the magnitude of P

surpluses or potential soil accumulations. In modern agricultural systems, P applications in either organic or inorganic forms are necessary to maintain the level of available P and change with both soil and plant types. McLaughlin et al. (1988) found that when applied P is taken up by the plant, it is either processed into organic P or becomes weakly adsorbed (physisorption) or strongly adsorbed (chemisorption) to Al, Fe, and Ca surfaces. Sharpley et al. (1994) found that many areas with intensive CAFOs, such as the Netherlands, Belgium, northeastern U.S., and Florida, now have soil P levels that are of environmental rather than agronomic concern.

Phosphorus Loss With Surface Runoff and Subsurface Drainage

McLeod and Hegg (1984) and Bushlee et al. (1998) found that control over P losses necessitates understanding the time and process factors, which are involved in P losses. They realized that differences in P transfer to water following an application of P amendment might be expected depending on the type of material applied. The loss of P in surface runoff is generally dominated by the movement with sediment PP as opposed to DP (Haygerth and Sharpley, 2000). Pietilainem and Rekolinen (1991) found that usually 60 to 90% of the P transported in surface runoff is associated with soil and organic matter transported as particles. Paul et al. (2001) studied the release of P to surface runoff following application of different P amendments to a dispersive silty clay loam soil. They found that the risk of P transfer to water sources from agricultural land fertilized with liquid and sewage sludge was less than when fertilized with either inorganic P fertilizer or liquid cattle manure due to the lower solubility of sludge P in water.

Lemunyon and Gilvert (1993) and Heathwaite (1997) found that the transport of soil P to water bodies depends on many factors including climate, soil type and hydrology, soil P

content, agronomic practices, and landscape position. Changes in the pathway and volume of runoff affecting P transport are related to the time of the year. The amounts of P entering a water body from diverse origins, as affected by the flow rate, have a huge impact on P concentrations in that water body. Sharpley et al. (1994) and Lennox et al. (1997) found that extended time of rainfall can result in P loss in soils and an increase in the risk of P transport to water bodies through leaching, erosion, and runoff processes; Edwards et al. (2000) collaborated that. It is not easy to determine the precise response of a particular reach of a stream to a land management because the land itself varies. They realized that the river system could be classified where individual river sections can be ranked according to their responsiveness to P.

As stated earlier, P moves in DP and PP forms. Pietilarnen and Rekolainen (1991) and Sharpley et al. (1992) observed that 60 to 90% of the P lost from cropland came during big storms. Youond and Ross (2001) noted that soils higher in P maintained greater floodwater PO_4-P concentrations and lower ratios of floodwater to pore water PO_4-P. The concentration of P was sustained in soils that were more highly saturated with P. Water escaping from soil covered by grass transports less sediment and contains considerably lower the concentrations of DP. It is important to realize that DP is directly available for biological uptake (Walton and Lee, 1972). Nurnbery and Peters (1989) also stated this as a finding in their studies. However, Wilding et al. (1974) and Corignan and Kalff (1986) affirmed that PP is a source for considerable amounts of P and could be damaging to the environment.

The quantity of P moving from catchments depends on hydrology, the areas where runoff originates, the content of P in the soil, and the amount of P added as fertilizer or manure. Most of the time it has been assumed that P is lost from croplands mainly during

surface runoff. It is known that in some regions like Florida, western Australia, and the Netherlands, most of P is lost through subsurface drainage waters. In most other areas, the P concentration in water infiltrating through the soil layer is reduced due to sorption of P by P deficient subsoils. In certain types of soils like acid organic soils, the adsorption is the main factor and the capacity for P the second, with the domination of negative (-) charged surfaces and the complexing of Al and Fe by organic matter. These interactions were carefully studied by Duxberg and Peverly (1978), Tuller (1979), and Whit and Thomas (1981).

Phosphorus transport via subsurface drainage is less well documented than that with surface runoff. This may be a result of both the difficulty in measurement and the general assumption that this pathway is quantitatively less important than surface delivery. Most subsurface transport of P is assumed to be in the soluble form, where typical concentrations of soluble P percolating through soil are of the order of 0.1 mg/L PO_4-P, even where soil P concentrations are high (Withers, 1994). Dils and Heathwaite (1996) reported that during a single storm event, the soluble inorganic fraction in subsurface drainage and near-surface flow contained only 10% of the total P exported in both undrained and tile-drained areas. Sharpley and Syers (1979) and Sharpley et al. (1992) found that for subsurface pathways, the link between land use and P export is less clearly defined than that for surface runoff. They also realized that below the ground surface, soil characteristics and P transformations along flow pathways become relatively more important in characterizing P loss.

Baker et al. (1975) found the annual P loss in subsurface drainage water was negligible because the P deficient subsoils could essentially fix all of the P moving from the plow-layer in drainage water. They recognized that P transported by leaching water could be a problem under certain conditions, such as poorly drained soils high in organic matter. P

concentrations in soil can affect concentrations in leaching water. Leaching water is another way of contributing P to surface waters in areas where subsurface drainage is significant. Some researchers in the Delmarva Peninsula have studied the movement of soil P to subsurface drainage waters with higher concentration of manure (Sims et al., 1997). Researchers in the Midwest and southeast are also dealing with the transport of P through the soil to tile drains at the same time as surface runoff (Sims et al., 1997). In Boone county, Iowa, dissolved inorganic P concentrations below 0.038 mg/L and the total P concentrations, including organic P and possibly P adsorbed on colloidal material, of 0.183 mg/L were found by Baker et al. (1975) in subsurface drainage water. The potential for groundwater contamination from P leaching does exist, especially if application rates of manure or chemical fertilizer are excessive and preferential flow of water through soil occurs. It is known that there are differences in P transfers that have been mostly related to site conditions and the effects of runoff volumes, rather than the differences in the relative P availabilities of the materials applied (Frossard et al., 1996).

Physical and Chemical Controls

There is a direct dependency between soil P content and the amount available for PP and DP loss in surface runoff. When the concentration of soil P increases, the amount of PP and DP transported also increases. Studies have proven that the P content and adsorption power of detached soil material is greater then that of in place source soil, due to preferential transport of finer less dense clay-sized material. It is important to realize that during a rainfall event, 1 to 5 cm of the soil layer on the surface interacts with rainfall and runoff (Sharpley, 1985). One of the reasons for this range is the relationship of rainfall and depth of soil involved in mixing is not easy to determine under natural conditions. There are

considerable dynamic factors related to the variability in rainfall intensity, soil tilth, and protective covers. A number of studies have been done in the areas of soil hydrology, topography, and management. The use of methods to protect against surface sealing by covering the soil surfaces with crop residue or reforestation was more suitable to alleviate the transport factors.

Dunningen and Dick (1980) studied the differences between the incorporation of P and surface application of P. The incorporation of P reduced P transfer and reduced differences in potential P release to runoff. In many cases, the soil disturbance caused by mechanical incorporation, with the absence of any crop cover, or under extreme rainfall intensities, can cause an increase of P transfer due to the accelerated transport of soil particles (Mostaghimi et al, 1992). Sharpley et al. (1986) have reported, based on several studies, that PO_4-P escaping soil by the erosion process is directly related to P transport from soil surface to fresh water body. They found that some states in the U.S. had similar linear relationships between the PO_4-P levels in runoff and soil test P levels (by Mehlich-3P) in the top 5 cm of soil from cropland and pastures. Sharpley (1993) found that iron oxide impregnated strips of filter paper could be used to evaluate the percentage of BAP in runoff water. If P behaves as a deposited element, iron oxide strips may have a more powerful theoretical basis then chemical extraction in estimating BAP. Sharpley (1995) reported that by using simulated rainfall (2.54 cm/h for 30 min) that iron oxide soil P was linked to BAP concentrations in runoff from some Oklahoma soils classified as sandy loam to clay in mineral composition. Van der Zea et al. (1987, 1990) and Breeuwsum and Silva (1992) noted that for Dutch soils, a critical P saturation of 25% was known for the threshold factor.

Most known point sources, e.g., hog confinement facilities and manure storages, may have high concentrations of dissolved P in their waste streams. However, most of the bioavailability studies have concentrated on PP, which is often the dominant factor in surface runoff from cropland. Equivalently, in Norwegian water samples, the proportion of reactive P often varied between 25 and 75% of the total P (Krogstad and Lovstad, 1998). Reactive P, measured by a moybdate method on unfiltered samples, was assumed to equal BAP.

Soil Phosphorus Management

In general, most of the countries in the world need a comprehensive and effective approach to avoid excess use of P in soil. P has a direct effect on the quality of water. Researchers in the Netherlands and Belgium have investigated the matter sufficiently to state that soil P values in some regions, those known for high animal densities, provide data/information to predict the optimal input of P to protect water quality (Breeuswma et al., 1995; Desmet et al., 1996; Schonumans et al., 1997; Schonumans and Groenerdick, 2000; Sibbesen and Sharpley, 1997; and Ven der Molen et al., 1998). Lawrance et al. (1985) noted that covered zones are usually used as a buffer or riparian areas around streams or water bodies to alleviate P inputs from agricultural land. In Finland, Rekolaiven (1989) found that P loss from protected soil and agriculture catchments during a series of samplings in the 1980's were higher than the series of samplings done in the 1970's. The author also observed that P use had increased from 20 kg/ ha/yr in 1965 to 35 kg /ha/yr in 1985. A 50% reduction in land under grass during the same period has been the main factor affecting P loads.

Studies relating agricultural to environmental P problems have provided some understanding of the mechanisms of dealing with soil P dynamics and release to water

escaping croplands. Less understood are spatial changes of P sources, unstable storages, and the hydrological movement within a catchment (Sharpley and Rekolainen, 1997). Kikham (1982), Melanen et al. (1985), and Mostaghimi et al. (1988) found that fertilizer P applications of sewage sludge might increase P transfer, especially at high application rates and/or under conditions of high runoff potential, compared with other P amendments. This is opposite of what Paul et al. (2001) found earlier. Many reasons exist for adopting nutrient management as a means of cutting costs and preserving water quality without jeopardizing yield goals. Environmental concerns, coupled with the demand for cost-effective agriculture, have heightened interest in developing innovative programs and plans for managing N, P, and potassium (K) nutrients contained in manure and commercial fertilizers. Brodie and Powell (1995) estimated that approximately 4,800 nutrient management plans (146,000 ha total area) were produced and 2,600 plans (85,000 ha) were updated in Maryland at a cost of about $22/ha or $670/plan. For those enrolled in the program, reductions in N and P use have been estimated at 57 and 40 kg/ha, respectively, resulting in a $52/ha saving. The soil resource can also benefit from proper nutrient management. For example, when practices such as timing and proper land-application rates of manure are incorporated into the plans, the quality of both surface and groundwater can be preserved (Edwards and Daniel, 1993 and Adams et al., 1994).

Another specific measure or practice to minimize P losses by erosion and runoff is planting vegetative filter strips (VFS) between agricultural areas and the water bodies into which those areas drain. VFS are bands of planted, or indigenous grass and/or fast-growing trees located down slope from croplands or other potential sources of nonpoint source pollution (NCASL, 1992). On the basis of observation of sediment deposition in grass strips

at the edge of grassed waterways, the potential to at least reduce soil loss exists. The success of this approach depends on the mechanisms by which P is transported from land to a water body. If the major P fraction is PP, or at least surface runoff-derived, buffer filter zones need to trap and retain sediment-associated P. In this case, factors such as the roughness coefficient of the vegetation in the buffer filter zone are critical. Vegetation characteristics will vary seasonally and it will be important to match maximum vegetation trapping efficiency with the main periods of P export.

Structural management practices for erosion and sediment control are designed and intended to operate without human intervention. However, some structural practices such as diversions, grassed waterways, and VFS may require some initial grading, shaping, and reseeding. VFS and field borders must be maintained to prevent channelization of water flow and the resulting short-circuiting of filtering mechanisms. Reseeding of buffer strips may be necessary on a frequent basis. Grazing and other livestock activities should be managed to avoid damage to vegetation cover, especially near streams (NCASL, 1992). An example of how VFS can be used in safeguarding water quality from nonpoint source of pollution is the Bear Creek Watershed Project in northeastern Story County in central Iowa (Hamilton, 2000). For nearly a decade, the Bear Creek watershed has been the site of a comprehensive research project designed by a team of researchers from Iowa State University. The purpose of the initiative is to demonstrate how VFS can filter out and assimilate nutrients such as N and P before they enter surrounding streams, prevent soil erosion, and stabilize stream banks. The project, now funded by federal, state, and private sources, shows that narrow grass strips of only 6 m wide can prevent more than 75% of nutrient and chemical runoff from reaching streams; wider strips that include trees can block

more than 90%. This project also demonstrates how farmers who value good land and water stewardship, can work together with scientists and governmental agencies to effect lasting environmental protection.

In many grassland catchments, livestock are often grazed on riparian land owing to its proximity to watering sites and the unsuitability of such land for other uses unless it is drained. Where this is the case, there is virtually no buffer between the land and the stream. This means that little transformation or trapping of P exported from the land is possible before P enters the stream. Runoff from grazed riparian areas may contain high concentrations of P in various forms - especially around feeding and watering areas (Heathwaite, 1993 and Dils and Heathwaite, 1996). Consequently, riparian land needs to be carefully managed to control P losses. The high risk of P loss from such zoned areas offers a good opportunity for effective nutrient export control, using a number of land-management options. These options commonly involve the use of buffer zones of various widths and designs and the control of fertilizer and livestock inputs within and close to such zones. Gbrired and Pionke (1995) found that the volume of runoff is a function of precipitation, temperature, soils, topography, groundwater, and moisture status over the catchment. They also mentioned that the role of water escaping from agricultural land is limited by soil water reserves rather than saturated capacity, which is greatly related to high water tables or soil water content. Sharpley and Syers (1979) mentioned that in conditions where only minimal runoff occurs, P movement is negligible.

Management of P in agriculture is currently more focused on the environment rather than the agronomic point in order of view to establish suitable P application rates and methods. In the U.S., environmental issues have obliged many states to develop and

implement recommendations for P application and management based on the concentration of P lost in runoff, and on the other hand, crop P requirements. The hard part to following these recommendations is when the soil test P levels above normal, which create a lot of concern for unacceptable levels of P loss in runoff. Most field evaluations of best management practice (BMP) effectiveness at reducing agricultural export of P conclude that nutrient management is the single most effective measure for controlling P losses (USDA-ASCS, 1992 and Beegle and Lanyon, 1994). This includes the use of regional soil testing programs that are flexible enough to accommodate differences among catchments, and development of manure management plans for CAFOs. In many areas, for example, soil P testing is not required with manure or fertilizer applications, and recommendations are still based on economic, not environmental, options.

Nutrient management plans should be established on a regional, rather than national, basis to cover areas with similar soil types and growing conditions. Several classification systems have defined such ecoregions (Bailey, 1983 and Omernik, 1987). Within these ecoregions, attainable water quality goals vary according to predominant land type and present use (Larsen et al., 1988). As a result, an ecoregional approach to nutrient management may be useful for characterizing attainable water quality goals. Also nutrient management interpretations and guidelines within these regions should be consistent (Gartlye and Sims, 1994). Often, inconsistencies in recommendations and interpretations over short distances can lead to farmers and producers questioning the reliability and philosophy of such plans, as well as a reluctance to use them. Farm advisers and extension agents are now instructing fertilizer users about the P content of manure and soil. Testing has confirmed that adding P rich manure to soil already high in P can create negative long-term effects in the

environment. The advisers and agents suggest farmers test their soil for P before applying fertilizer.

P is a major nutrient, along with N and K, and plays a key role in maintaining beneficial and profitable crop production. The use of excess P and loss with land drainage can cause considerable damage to surface water resources. Some sources of P include animal manures, agricultural fertilizers, and municipal sewage. In the area where the main objective is to maintain profitability of crop production, with less emphasis on environmental issues, P losses from agriculture land can be a principal source of the P entering lakes, rivers, and streams (Sharpley and Rekolainen, 1997). Dominant factors of P loss from agricultural lands and movement to surface water are of two types: those relating to transport and carriers and, those relating to source and concentrations (Pietilainen and Rkolainen, 1991 and Sharpley et al., 1992). Eghball (1999) found that the main factors controlling P movement in surface runoff are transport (runoff volume and erosion amount) and source factors (such as application method, timing, rate of manure of fertilizer, and P fertility or test level in the soil).

Sharpley and Sims (1999, 1986) found that manure application is often based on the N needs of the crop being grown. Long-term application of manure with too much P relative to N results in increased concentrations of P in soils above the range necessary for optimum crop growth, and also results in increased concentrations of P in surface runoff and subsurface drainage water. This issue is critical in regions with sensitive water resources located near CAFOs or intensive farming activities (Edwards and Daniel, 1992; McLoed and Hegg, 1984; and Sharpley, 1999). When elevated soil P levels coincide with zones of surface runoff, elevated soil P levels can account for most of the total annual P lost to water bodies

(Cooper et al., 1984). Baker et al. (1975) found that the average soluble P concentration in ten tile drains in an intensively farmed area was about 0.09 mg/L, whereas surface runoff from corn and soybean fields and a pasture in the same area averaged 0.38 and 0.96 mg/L, respectively. Most previous research and nonpoint source control efforts have emphasized P losses with surface runoff and erosion because of the relative immobility of P in soils (Fulhage, 1993; Giddens and Barnett, 1980 and; Westerman et al., 1988). Consequently, P leaching and losses with subsurface drainage water have rarely been considered important pathways for the movement of agricultural P to surface waters. But there are situations where environmentally significant leaching of dissolved organic P in the soil profile of agricultural lands has occurred. For example, intensively cultivated soils, deep sandy soils, high organic matter content soils, or soils with high P concentrations from long-term over fertilization or excessive use of manure have the potential of leaching dissolved P to subsurface drain water (Hechrath et al., 1995; Ron Vaz et al., 1993; and Sims and Wolf, 1994).

Morgan (1997) found that while the precise sequence of events that follow from an application of soluble fertilizer to soils is unclear; there is a general consensus as to the principal components of the retention process. These are: (i) events associated with the dissolution of the P fertilizer particle; (ii) the occurrence of precipitation reactions involving the PO_4-P anion, in which both reactants are initially dissolved in the soil solution; and (iii) the occurrence of adsorption reactions, in which only one of the reactants is initially in solution. Losses of DP in water runoff are a function of both runoff water volume and DP concentration. The managed factors that may contribute to DP losses are soil P status, P

fertilizer application, subsurface drainage, and grazing by domestic animal (Gillingham and Thorrold, 2000).

The U.S. Environmental Protection Agency (EPA) indicated that agriculture is the leading contributor to water quality impairments to surveyed rivers and lakes, the third largest source of impairments to surveyed estuaries, and also a major contributor to groundwater contamination and wetlands degradation. One question is whether excess P application and P buildup in the soil can occur within limits without significant water quality problems. Or, if surface water quality is the only concern, what management practices (some affecting the rainfall energy reaching the soil surface) can be used to possibly alleviate the concerns? Koswara and Hanway (1969) placed much emphasis on the use of the chemical soil test in the state of Iowa to provide and guide the indexes of P availability to plants.

The overall objective of this study was to determine factors that cause or contribute to P transport with sediment and water in surface runoff and subsurface drainage.

The specific objectives of this study were to determine:

1. how soil available P levels are increased with added P for three Iowa soils (Nicollet, Marshall, and Fayette),
2. how orthophosphate-P (PO_4-P) and total-P concentrations in surface runoff are affected by the added P for these soils,
3. how the hydrology and P concentrations and losses are affected with the Nicollet soil when rainfall energy is dissipated by a screen, and
4. how added P affects P concentrations and losses for water draining through a thin layer of soil.

CHAPTER 3. MATERIALS AND METHODS

The National P Project Protocol for Indoor Runoff Boxes was used in developing procedures for this rainfall simulation study. This protocol describes a laboratory method to relate soil P to P concentrations in surface runoff. This procedure allows for the estimation of P extraction and entrainment, as well as identification of transport processes affecting the transfer of P from soil to runoff (either in water or sediment phases) on a relative basis. The protocol is designed to control a variety of potentially confounding factors, such as spatial and hydrologic variability, but is not designed to represent absolute edge-of-field concentrations. The protocol described is for cropped land, conventional-tilled (seedbed) conditions, not pasture or non-tilled land. Results from the above protocol should relate to field results, yet the protocol cannot and does not need to duplicate field conditions. Field plots should be used to address more than just the relationship between soil P and surface runoff P (e.g., hydrologic response of soil to rainfall). Relationships developed from the runoff box protocol should eventually be tested and compared to field data.

Rainfall Simulation and Sampling

The protocol used in this research closely followed the field protocol of the "Benchmark Soils Project." Runoff boxes were set at a 4% slope and rainfall was applied at 6.5 cm/h. Runoff samples were taken with time during the rainfall simulation from the point in time when runoff started, with sediment and runoff water passed through plastic tubes to a beaker on a balance that was connected to a data logger. The beakers used for runoff collection were changed when the runoff volumes reached 800-900 mL at nearly uniform time intervals

(generally 3 to 4 min). The sediment and water mixtures were poured into clean jars, weighed, and the mass recorded. Boxes were run in pairs, with ten to

fourteen runoff samples collected for the screen covered box (only during the runs with the Nicollet soil) and 20 samples were collected for the uncovered boxes for each simulation. The subsurface sample collection was facilitated by the use of the vacuum; it was applied 24 min after rainfall stated for the first soil and turned off at 74 min (as shown in Figure 3) for the second soil it was started at 24 min after rainfall simulation started and turned off after 74

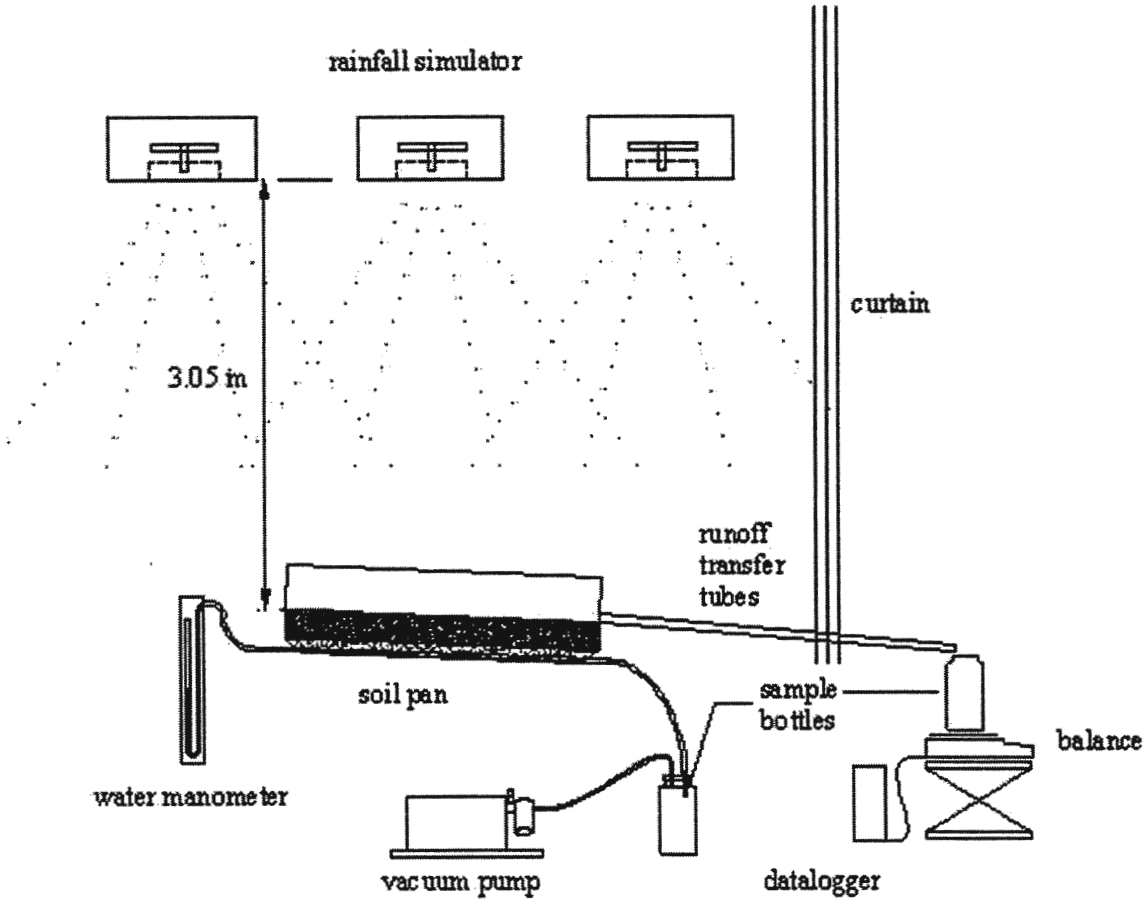

Figure 1. Runoff and subsurface collection apparatus

min (as shown in Figure 4). Runoff volume, sediment yield, and P concentration and losses were measured as defined under the field protocol.

Soil Collection

Soil samples were collected from three different plots on experimental farms in the state of Iowa starting in the fall of 1999 and finishing in the summer of 2000. These sites were chosen to provide different soil samples with a wide range of pH, available P, and other soil characteristics. The locations sampled represent three of the major soil associations. Plot treatment and cropping history for the Nicollet soil was corn-soybean rotation, chisel-plow/field cultivation tillage since 1976, and unknown before that. For the Marshall soil, it was corn-soybean rotation, chisel-plow/field cultivation tillage since 1993, continuous corn from 1984 to 1992, unknown before that, and for the Fayette soil, it was corn-soybean rotation, chisel-plow/field cultivation tillage since 1990. Most of the fields had been plowed when they were sampled. The sampling method was essentially the same as that described by Isobe (1966). About 1000 kg of soil were collected from the plow layer (0-15 cm depth) from each chosen plot. After large roots and distinguishable plant residues were removed, un-dried soil was screened using 1.3 cm sieves. This dimension of sieve was considered satisfactory for obtaining a reasonable degree of fineness without appreciably destroying the original soil structure. Each soil sample was mixed thoroughly in a small, portable cement mixer, and then stored in a plastic container. The sieved soil was analyzed for the background level of available P, total P, pH, moisture content, soil organic matter content, and particle size. The average soil moisture content for the soil when packed in the boxes was 9.51% on a dry-weight basis; the bulk density was 1.1 g/cm^3.

Sample Analysis

Water samples were analyzed for PO_4-P and total-P (including sediment) concentrations by using the ascorbic acid method (Arnold et al., 1992), after extraction or digestion.

Determination of total-P on unfiltered samples was performed according to EPA method 351.2 (EPA, 1993) by digesting 20 mL samples with 10 mL of a mixture made up from concentrated H_2SO_4, K_2SO_4, and $CuSO_4$ for 1 h at 160° C and then 1.5 h at 380° C until 1-2 mL was left. Samples were then diluted to 50 mL with deionized water and analyzed for PO_4-P.

P Additions and Incubations

The treatments were five different levels of added P: 0, 50, 125, 300, and 600 ppm on a dry-weight-of-soil basis. These treatments are designated P_0, P_1, P_2, P_3, and P_4, respectively, and those symbols will be used throughout this discussion. The treatments were replicated three times. The P treatments were applied to soil previously sieved and mixed. The mixing was done inside a small, portable cement mixer. The P fertilizer was added as a water solution of monobasic ammonium phosphate (MAP). For each level of added P (50, 125, 300, and 600 ppm) stock solutions were prepared and designated as P_1, P_2, P_3, and P_4, respectively. After 45 min of adding and mixing water containing MAP with the soil, the mixture was transferred to a plastic bag and stored inside a plastic container located indoors for 30 days.

Runoff Box Construction

Plastic lids of large containers were used as runoff boxes. The dimensions of the plastic lids were 82.5 cm long by 42.3 cm wide. Twelve cm sideboards were attached at the

upper rim of each box to reduce water and sediment loss due to raindrop splash. These sideboards caused the dimensions of the rainfall collection surface area to decrease to 81.8 cm long by 39.2 cm wide (3207 cm^2). The boxes were run in pairs for each rainfall simulation. For the Nicollet soil, one of the boxes would be covered with a window screen. A 0.95 cm inside diameter perforated polyethylene drain tube was inserted into the bottom of each box to serve as a subsurface drain. Figure 2 provides specific dimensions and characteristics of the runoff boxes. Prior to simulation, each box was positioned at an approximate 4% slope. For one box when running the Nicollet soil, a fiberglass window screen was placed over the runoff

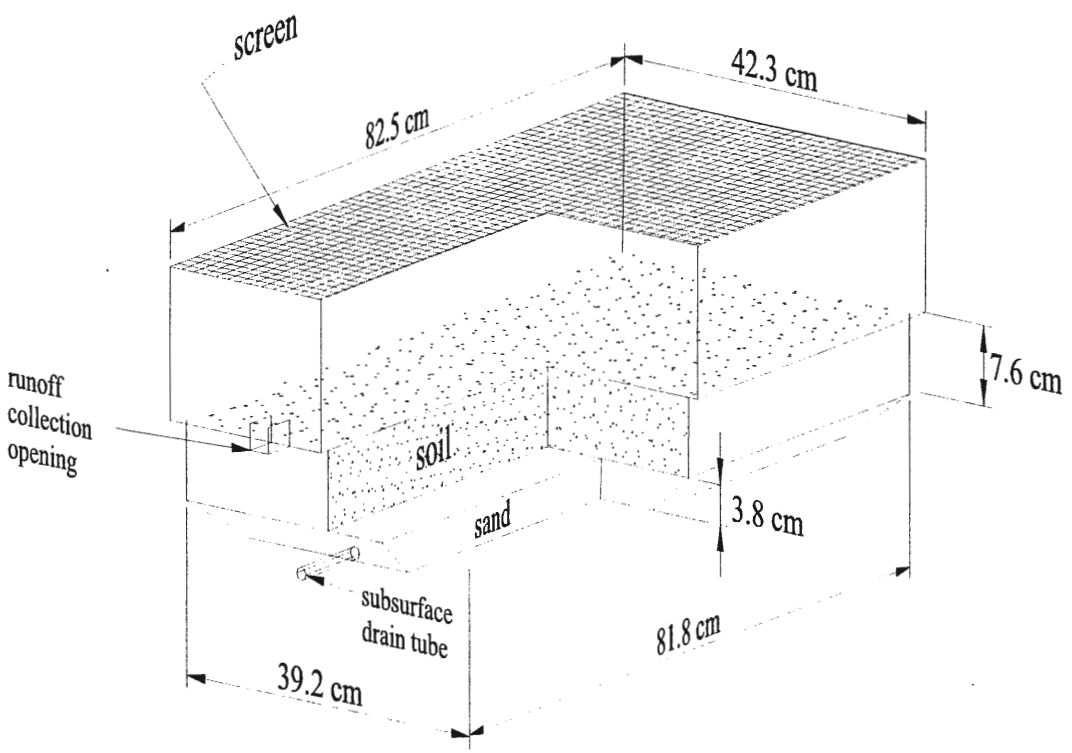

Figure 2. Schematic diagram of soil box.

box above the soil in order to dissipate rainfall energy. The boxes were positioned a minimum 3.05 m below the rainfall simulator nozzles.

Packing the Boxes with Soil

The soil was packed in the boxes in layers (as described below) with a predetermined weight of the soil so that the final weight of soil in the box was known, and the approximate bulk density of field soil of 1.1 g/cm^3 could be achieved. Five cm of fine silica sand was placed on the bottom of the box to a depth of 3.8 cm, followed by cheesecloth and a window screen. Above the sand, three predetermined equal masses of soil were compacted in three successive layers to a total thickness of 7.6 cm, resulting in a dry bulk density of 1.1 g /cm^3. The added soil was level with the lower lip of the runoff boxes. Once filled, the runoff boxes were vibrated for 5 min to promote settling without destroying the remaining peds. A small amount of soil was added to the boxes until it was again level with the lower lip of the box. After the desired bulk density and level were achieved, the boxes were placed below the rainfall simulator. Before rainfall simulation, samples of the soil were taken for gravimetric soil moisture content determination.

The statistical analyses were performed on SAS using PROC GLM. There were multiple comparisons of LS means used in analyzing this data. The Tukey-Kramer test was used to properly account for the effects of added P and of the Nicollet, Marshall, and Fayette soils (with and without screen only for Nicollet).

CHAPTER 4. RESULTS AND DISCUSSION

Laboratory Results

The soil types sampled, and a description of some physical and chemical properties of the soil samples used in this study, are reported below. The Nicollet soil consisted of 38.7% sand, 16.6% coarse silt, 20.6% fine silt, and 24.1% clay with total carbon (TC) 2.77%, Ca 3332 ppm, K 202 ppm, Mg 415 ppm, and total-P 437 ppm, in the top 0-15 cm. The average pH was between 5.3 to 6.0, and available P was 14.9 ppm as Bray P-1. The Marshall soil consisted of 3.4% sand, 38.2% coarse silt, 30.9% fine silt, 27.6% clay, TC 2.35%, Ca 3282 ppm, K 397 ppm, Mg 355 ppm, and total-P 515 ppm; pH was between 5.4 to 7.1, and available P was 23.6 ppm. The Fayette soil consisted of 5.6% sand, 39.2% coarse silt, 29.2% fine silt, and 26% clay, TC 1.31%, Ca 1887 ppm, K 123 ppm, Mg 608 ppm, and total-P 374 ppm; pH was between 3.37 to 6.28, and available P was 7.5 ppm. Thus, the physical and chemical properties of the different soils showed wide variations. There was no consistent relationship between the other soil characteristics and the initial level of available P as measured by the Bray P-1 test.

Additions of P to the soils resulted in similar rates of increase in the Bray P-1 soil test values for all three soils in 30 days. An extension of incubation time might have decreased the concentration of available P even further, but only one measurement was made. This effect was nearly linear and thus similar for all four rates of added P; the intercept of the linear relationship was nearly equal to the background level of P in the original soil. Reaction of the added P with the soils was fairly rapid: only from 71 to 77% could be

measured as available P for the Nicollet soil, 66 to 75% for Marshall soil, and 45 to 79% for the Fayette soil after 30 days of incubation.

Table 1 shows average surface runoff depths and the concentrations and losses of PO_4-P, total-P (of total runoff sample, water and sediment), and sediment in surface runoff for boxes with and without a screen for the Nicollet soil under different levels of added P. As shown, P concentrations and losses were consistently lower in surface runoff from the box with the screen than for the box without the screen. The screen over the box caused less hydraulic penetration of raindrops into the soil surface that decreased the depth of the mixing zone, and in turn resulted in less extraction of PO_4-P into surface runoff. As also shown in Table 1, reduced rainfall energy with the screen reduced soil detachment and sediment concentrations and losses. The screen also decreased surface runoff volumes.

The results in Table1 show that when the level of added P increased, the P concentrations and losses increased. Statistical comparisons are given in Table 1 for runoff depth and PO_4-P, total-P, and sediment concentrations and losses. The results indicated that increases in application rates of added P resulted in significantly higher PO_4-P and total-P concentrations and losses in surface runoff for boxes both without and with a screen cover. Somewhat surprisingly, for some data sets, sediment concentrations decreased with increased added P, which might be interesting for future study. Statistical analysis of the results showed that there was a significant difference in surface runoff depth between the boxes without (average of 5.8 cm) and with the screen (average of 3.01 cm). Table 2 shows, parallel to Table1, the average subsurface drainage depth and flow-weighted concentration and losses of PO_4-P, total-P, and sediment in subsurface drainage water for the Nicollet soil without and with a screen. P concentrations were generally higher in subsurface drainage compared to

surface runoff. The screen treatment helps protect the soil against sealing and maintains a higher water infiltration rate due to its protection of the soil surface against rainfall drop impact. It was noticeable that P concentrations in the subsurface drainage increased with the increase of the P added. In general, the highest subsurface concentrations for PO_4-P and total-P were with the screen, but sediment concentrations were lower with the screen. Contrary to surface runoff, concentrations for PO_4-P and total-P in subsurface drainage were sometimes higher in subsurface drainage for the tray with the screen, and P losses were all higher with the screen. Losses were higher in part because of more flow with the screen (average of 1.70 cm) compared to without (average of 0.26 cm

Table 3 gives the surface runoff results for the Marshall soil rainfall simulation. The screen treatment was included for only the P_0 level for the Marshall soil because the results from previous simulations for the Nicollet soil showed only small absolute differences in P concentrations. The data shows application of P resulted in statistically higher concentration and losses of PO_4-P, and total-P, similar to the Nicollet soil.

Table 4 shows average subsurface drainage depths, and the concentrations and losses of PO_4-P, total-P, and sediment in subsurface drainage water for boxes without a screen for the Marshall soil for different levels of added P, and with a screen for no added P. The influence of the rainfall energy on soil without a screen seals the soil surface, while with the screen, rainfall energy impact on the soil is reduced which lowers the runoff amount, but increases the subsurface drainage volume and P losses. As the added P increases so did the concentrations and losses of PO_4-P and total-P.

Table 5 shows the average surface runoff depths and the concentrations and losses of PO_4-P, total-P, and sediment for the Fayette soil. As with the Nicollet and Marshall soils, the P concentrations increased with the level of added P.

Table 6 shows the average concentrations of PO_4-P, total-P, and sediment in subsurface drainage water for the Fayette soil. The results show that an increase in added P resulted in an increase in the concentrations of PO_4-P, total-P, and sediment. It is observed that sediment concentrations were lower for subsurface drainage compared to surface runoff, which may be due to the filtration process through the soils and sand layers inside the box.

Table 7 shows average surface runoff depths, with statistical analysis, for Nicollet, Marshall, and Fayette soils and for boxes with and without a screen (for the Nicollet soil) under different levels of added P. As shown, the runoff depths were consistently lower from the box with the screen than from the box without screen. The screen over the box reduced rainfall energy and potential surface sealing that in turn resulted in decreased surface runoff volumes. As also shown in Table 7, reduced rainfall energy with the screen reduced soil detachment and sediment concentrations.

Table 8 shows average flow-weighted concentrations of PO_4-P in runoff water for all the soils. The results of the statistical analysis show that there were significant differences among all treatments and soils. For instance, the Nicollet soil without screen cover released more PO_4-P than that with screen with the exception of the P_0 treatment. All three soils (without cover) responded similarly in releasing PO_4-P into runoff water.

Table 9 gives the average loss of PO_4-P with runoff water as a function of screen treatment and soils. A statistical analysis of the results indicated that there were significant

differences in PO_4-P loss, with the boxes without covers giving the highest losses. As with PO_4-P concentrations, losses among the three soils were similar.

Table 10 shows the average flow-weighted concentrations of total-P in runoff water from the boxes (with and without cover) as a function of added P. Statistical analysis of results showed that there was a significant difference between the two boxes; the box without a cover had the higher total-P concentration. This difference is caused by the screen that dissipated the raindrop energy. There was a trend for the Marshall soil to have the highest total-P concentrations of the these soils studied.

Tables 11, 12, and 13 show parallel results for total-P loss in surface runoff, concentrations of sediment, and sediment losses. Total-P losses were greatest without the screen, but differences between soils were inconsistent. All the boxes without screens released more sediment into runoff water in terms of both concentrations and losses. There was a weak trend of lower sediment concentrations and losses for the Nicollet soil.

Table 14 shows average subsurface drainage depths, contrary to surface runoff, the effect on depth was more pronounced with the cover treatment having more drainage. Statistical analysis of the results showed that there was a significant difference between soils, although it was not large on absolute magnitude losses.

Table 15 shows the flow-weighted concentrations of PO_4-P in subsurface drainage. It shows that subsurface drainage concentrations of PO_4-P were sometimes higher with screen than without. Among the soils, results were mixed.

Tables 16, 17, 18, 19, and 20 show PO_4-P losses, total-P concentrations, total-P losses, sediment concentrations, and sediment losses in subsurface drainage. In the

comparisons between the two screen treatments (with and without), the statistical results show that generally losses, but not concentrations, were greatest with the screen.

The results in Table 21 show the parameters (slopes and intercepts) for linear regressions for PO_4-P and total-P concentrations in surface runoff versus available P. The parameters are slightly different from each other, which may be due to different soil characteristics. For example, the intercept depends on the initial available P concentrations. Table 22 shows the soil property data and added P results after incubation.

Figures 3 and 4 show examples of the hydrology of two simulation runs versus time and the effect of without and with screen on surface and subsurface drainage. The use of a screen on the top of the soil delayed and decreased surface runoff, but speeded up and increased subsurface drainage.

As shown in Figure 5, the average available P in the Nicollet soil increased as the amount of added P increased. The figure also shows that the amount of added P and available P were highly correlated ($r^2 = 0.999$). Similar results were observed by Koswara and Hanway (1969). A similar correlation can be observed in Figure 6 for the Nicollet soil between PO_4-P in surface runoff and available P, without and with the screen treatment. The correlation between the two was highly significant, $r^2 = 0.993$ without screen and $r^2 = 0.999$ with screen. As shown in Figure 7, the amount of total P released into runoff was higher without the screen than with the screen. Figure 8 shows that the correlations of PO_4-P in surface runoff with added P are very similar to those for available P as would be expected because of the close correlation between available P and added P. The rate of increase of concentrations of PO_4 -P in surface runoff for boxes without the screen is larger than that of the boxes with the screen. Figure 9 shows results for total P versus added P parallel those

for PO_4-P. Figure 10 shows PO_4-P concentrations in subsurface drainage and that the result of with screen and without screen was parallel when the concentrations of the PO_4-P were plotted against added P. Figure 11 shows total-P concentrations versus added P. The concentrations increase with amount of added P. In all cases, the correlations between added P remained very high. Figures 12 and 13 show that concentrations of available P versus PO_4-P and total-P in subsurface drainage is different with and without a screen and when compared to runoff concentrations.

Three soils samples representing a wide range in chemical and physical properties found in most of the soils in Iowa were included in this study. The Nicollet soil, Marshall soil, and Fayette soil did not respond differently to added P; the correlations among the soils were all very similar (see Figures 5, 14, and 23). The results of the incubation experiment indicated that all the soils behave similarly to the recovery process and P increases (see Table 8). Overall, the without screen treatment had more influence on unprotected soils due to the energy influence in bare soils.

Figure 14 shows available P versus added P for the Marshall soil. The relation between available P and added P was highly significant ($r^2 = 0.995$). A separate correlation was calculated with available P versus PO_4-P, total-P, and sediment concentrations. In all cases, the correlation between concentrations and available P remained very high. Figures 15 and 16 show available P versus PO_4-P and total-P concentrations in surface runoff. The correlations between PO_4-P and total-P concentrations in subsurface drainage and available P were similar. (Figures 17 and 18). Figure 19 shows the relationship between PO_4-P and added P, which gave r^2=0.937 for the Marshall soil. As added P increased, total-P also increased with r^2= 0.928 (see Figure 20). Figure 21 shows added P versus PO_4-P in

subsurface drainage for the Marshall soil. This relationship gave $r^2 = 0.904$. Figure 22 shows added P versus total-P in subsurface drainage for Marshall soil with $r^2 = 0.854$.

Figure 23 shows a good relationship between added P versus available P for Fayette soil with $r^2=0.982$. As available P increased, PO_4-P concentration in subsurface drainage also increased, with $r^2=0.996$ (Figure 24). Figure 25 shows the relationship between available P versus total-P in surface runoff for the Fayette soil which gave $r^2= 0.986$. The results obtained from Figure 26 shows a good relationship between available P versus PO_4-P in subsurface drainage with $r^2= 0.940$. Similar results are obtained in Figure 27, with subsurface drainage with $r^2=0.904$. Figures 28, 29, 30, and 31 showed a high correlation between added P versus PO_4-P and total-P in surface water and subsurface drainage for the Fayette soil.

Figures 32 and 33 show average flow-weighted concentrations of PO_4-P versus time in surface runoff and subsurface drainage with and without a screen for the Nicollet soil. The figures show that the concentration of PO_4-P decreased with time in surface runoff and usually increased with time in subsurface drainage. The P concentrations in subsurface drainage from the box with the screen were higher than the box without the screen. The opposite occurred for the surface runoff samples. The lower runoff concentrations for the box with the screen may have resulted from the less hydraulic penetration of rainfall (with less energy) into the thin soil surface-mixing zone. Figures 34 and 35 show the differences in sediment concentrations in surface runoff and subsurface drainage with and without a screen for the Nicollet soil versus time. It is interesting to see that runoff started later with the box with a screen. The concentrations of sediment transported with surface runoff were very different between the box with the screen and the one without. Figures 36 and 37 show the

differences in time verses total-P concentrations for boxes with and without screen for the Nicollet soil. The time to runoff was longer and the runoff volume was less for the box with the screen. Again, the total-P concentrations were lower with the screen treatment and therefore, so were the losses. The subsurface drainage concentrations were generally higher with the screen treatment due to the effect of the screen, which influenced the rain energy on the bare surface.

Figures 38 and 39 show PO_4-P and total-P concentrations verses time for the Marshall soil. These figures show the data for the average flow-weighted concentrations for PO_4-P and total-P in surface runoff and subsurface drainage water for the Marshall soil. Figures 40, 41, and 42 show the flow-weighted concentrations of PO_4-P, sediment, and total-P in surface runoff and subsurface drainage water for the Marshall soil versus time. Figures 43, 44, and 45 show the flow-weighted concentrations of PO_4-P, total-P, and sediment P in surface runoff and subsurface water for the Fayette soil versus time. The P concentrations in each figure decrease with time presumably as the amount of P in the mixing zone that is available to be lost decreases; however, the subsurface concentrations remain very high, particularly for total-P.

Table 1. Average surface runoff depth and flow-weighted concentrations and losses of PO_4-P, total-P, and sediment in runoff water: Nicollet soil

			PO_4-P		Total-P		Sediment	
Trt	n	Water depth	Conc.	Loss	Conc.	Loss	Conc.	Loss
		cm	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
Without Screen								
P_0	3	4.92b*	0.055c	0.027d	1.710b	0.842c	2870a	1412c
P_1	3	5.68a	0.134c	0.076d	1.922b	1.093c	2824a	1604b
P_2	3	6.27a	0.272b	0.170c	1.970b	1.235b	2736b	1715a
P_3	3	6.16a	0.607a	0.374b	3.240a	1.997a	2833a	1745a
P_4	3	5.97a	0.995a	0.594a	3.880a	2.328a	1877c	1126d
With screen								
P_0	3	3.15a*	0.057d	0.018d	1.00b	0.315c	1762a	555a
P_1	3	2.88b	0.118c	0.034d	0.882c	0.254d	1438c	414b
P_2	3	3.44a	0.216c	0.074c	1.284b	0.441b	1503b	517a
P_3	3	3.09a	0.455b	0.140b	1.495b	0.462b	1513b	467b
P_4	3	2.53b	0.822a	0.208a	2.245a	0.567a	1406c	355c

*Means with the same letter for each variable for the five P treatments are not significantly different at significance level of $p = 0.05$.

Table 2. Average subsurface drainage depth and flow-weighted concentrations and losses of PO_4-P, total-P, and sediment in subsurface drainage water: Nicollet soil

			PO_4-P		Total-P		Sediment	
Trt	n	Water depth	Conc.	Loss	Conc.	Loss	Conc.	Loss
		cm	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
Without Screen								
P_0	3	0.349a*	0.085d	0.003c	0.419d	0.015c	3880a	135a
P_1	3	0.306a	0.237c	0.007c	0.519d	0.016c	3773a	115b
P_2	3	0.213b	1.733b	0.036b	2.956c	0.062c	1308b	28d
P_3	3	0.136c	2.237b	0.030b	26.300b	0.353b	1288b	17e
P_4	3	0.316a	3.717a	0.117a	74.910a	2.369a	1004c	32c
With screen								
P_0	3	1.78a	0.085c	0.015c	0.343d	0.061d	3218b	573b
P_1	3	1.94a	0.293c	0.056c	0.707d	0.137d	2275c	441c
P_2	3	1.52a	2.118b	0.321b	3.324c	0.505c	3867a	588b
P_3	3	1.45a	3.770a	0.546a	36.8b	5.336b	3662a	5802a
P_4	3	1.85a	3.557a	0.658a	49.34a	9.127a	1939c	359c

*Means with the same letter for each variable for the five P treatments are not significantly different at significance level of $p = 0.05$.

Table 3. Average surface runoff depth and concentrations and losses of PO_4-P, total-P, and sediment in runoff water: Marshall soil

			PO_4-P		Total-P		Sediment	
Trt	n	Water depth	Conc.	Loss	Conc.	Loss	Conc.	Loss
ppm		cm.	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
Without Screen								
P_0	3	5.74b*	0.060c	0.036c	1.756c	1.007c	3188b	1830c
P_1	3	5.42b	0.133b	0.072c	3.05b	1.622b	3171c	1718d
P_2	3	6.27a	0.444b	0.278b	3.67b	2.302a	4186a	2625b
P_3	3	4.46c	0.931a	0.415a	4.20b	1.871b	3727a	1662a
P_4	3	6.12a	1.017a	0.622a	6.18a	3.782a	3657a	2238c
	With screen							
P_0	3	4.35	0.031	0.013	0.30	0.13	2025	881
P_1	3	-	-	-	-	-	-	-
P_2	3	-	-	-	-	-	-	-
P_3	3	-	-	-	-	-	-	-
P_4	3	-	-	-	-	-	-	-

*Means with the same letter for each variable for the five P treatments are not significantly different at significance level of $p = 0.05$.

Table 4. Average subsurface drainage depth and concentration and losses of PO_4-P, total-P, and sediment with subsurface drainage: Marshall soil

			PO_4-P		Total-P		Sediment	
Trt	n	Water depth	Conc.	Loss	Conc.	Loss	Conc.	Loss
ppm		cm	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
Without Screen								
P_0	3	0.428b*	0.059c	0.002c	0.22c	0.009c	3720b	112b
P_1	3	0.437b	0.208c	0.009c	0.425c	0.018c	4139a	182b
P_2	3	0.382c	0.497b	0.018b	14.61b	0.555b	3791b	144b
P_3	3	0.627a	0.557b	0.034b	26.64a	1.651a	188.3c	12d
P_4	3	0.516a	2.50a	0.127a	32.06a	1.635a	5377a	274a
With screen								
P_0	3	4.59	0.62	0.28	14.10	6.47	1947	894
P_1	3	-	-	-	-	-	-	-
P_2	3	-	-	-	-	-	-	-
P_3	3	-	-	-	-	-	-	-
P_4	3	-	-	-	-	-	-	-

*Means with the same letter for each variablefor the five P treatments are not significantly different at significance level of $p = 0.05$.

Table 5. Average surface runoff depth and concentrations and losses of PO_4-P, total-P, and sediment in runoff water: Fayette soil

			PO_4-P		Total-P		Sediment	
Trt	n	Water depth	Conc.	Loss	Conc.	Loss	Conc.	Loss
ppm		cm	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
Without Screen								
P_0	3	6.72a*	0.050d	0.033d	1.193c	0.801c	3301a	2218a
P_1	3	6.87a	0.125c	0.085c	1.716c	1.180b	3384a	2327a
P_2	3	6.79a	0.267c	0.181c	1.772c	1.203b	3085a	2094a
P_3	3	7.69a	0.603b	0.463b	2.536b	1.949b	2964a	2279a
P_4	3	7.43a	1.362a	1.012a	4.450a	3.306a	3205a	2381a

* Means with the same letter for each variable for the five P treatments are not significantly different at significance level of $p = 0.05$.

Table 6. Average subsurface drainage depth and concentrations and losses of PO_4-P, total-P, and sediment subsurface drainage water: Fayette soil

			PO_4-P		Total-P		Sediment	
Trt	n	Water depth	Conc.	Loss	Conc.	Loss	Conc.	Loss
ppm		cm	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
Without Screen								
P_0	3	0.134b*	0.821c	0.011b	23.36b	0.313b	1546b	21 b
P_1	3	0.096b	1.177b	0.011b	24.8b	0.238c	1545b	15c
P_2	3	0.087b	1.785b	0.016b	27.23b	0.236c	2424a	21b
P_3	3	0.067b	1.666b	0.011b	33.95a	0.227c	709c	5d
P_4	3	0.220a	3.316a	0.072a	36.2a	0.796a	2791a	61 a

* Means with the same letter for each variable for the five P treatments are not significantly different at significance level of $p = 0.05$. and total-P

Table 7. Average surface runoff depth.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	----------	----------	----------	cm ----------	----------	----------
P_O	3.15c*	4.92b	-	5.74b	-	6.72a
P_1	2.88c	5.68b	-	5.42b	-	6.87a
P_2	3.44b	6.27a	-	6.27a	-	6.79a
P_3	3.09c	6.16b	-	4.46c	-	7.69a
P_4	2.53c	5.97b	-	6.12b	-	7.43a

*Means with the same letter across rows for each variable are not significantly different at significance level of $P = 0.05$; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 8. Average flow-weighted concentrations of PO_4-P in runoff water.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	---------- mg/L ----------					
P_O	0.057a	0.055a	-	0.060a	-	0.050b
P_1	0.118b	0.134a	-	0.133a	-	0.125b
P_2	0.216b	0.272a	-	0.444a	-	0.267b
P_3	0.455c	0.607b	-	0.931a	-	0.603b
P_4	0.822c	0.995b	-	1.017b	-	1.362a

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 9. Average loss of PO_4-P with runoff water.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	---------- kg/ha ----------					
P_O	0.018b	0.027a	-	0.036a	-	0.033a
P_1	0.034b	0.076a	-	0.072a	-	0.085a
P_2	0.074c	0.170b	-	0.278a	-	0.181b
P_3	0.140b	0.374a	-	0.415a	-	0.463a
P_4	0.208c	0.594b	-	0.622b	-	1.012a

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 10. Average flow weighted concentrations of total P in runoff water.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	---------- mg/L ----------					
P_O	1.000b	1.710a	-	1.756a	-	1.193b
P_1	0.882c	1.922b	-	3.05a	-	1.716b
P_2	1.284c	1.970b	-	3.67a	-	1.772b
P_3	1.495c	3.240b	-	4.20a	-	2.536b
P_4	2.245c	3.880b	-	6.18a	-	4.450b

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 11. Average loss of total-P with runoff water.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	kg/ha					
P_0	0.315b	0.842a	-	1.007a	-	0.810a
P_1	0.254b	1.093b	-	1.622a	-	1.180b
P_2	0.441c	1.235b	-	2.302a	-	1.203b
P_3	0.462b	1.997a	-	1.871a	-	1.949a
P_4	0.567c	2.328b	-	3.782a	-	3.306a

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 12. Average flow weighted concentrations of sediment in runoff water.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	mg/L					
P_0	1762b	2870a	-	3188a	-	3301a
P_1	1438b	2824a	-	3171a	-	3384a
P_2	1503c	2736b	-	4186a	-	3085b
P_3	1513b	2833a	-	3727a	-	2964b
P_4	1406d	1877c	-	3657a	-	3205b

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 13. Average loss of sediment with runoff water.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	kg/ha					
P_0	555d	1412c	-	1830b	-	2218a
P_1	414c	1604b	-	1718b	-	2327a
P_2	517c	1715b	-	2625a	-	2079b
P_3	467c	1745b	-	1662b	-	2279a
P_4	355c	1126b	-	2238a	-	2381a

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 14. Average subsurface drainage depth.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	---------- cm ----------					
P_O	1.78a	0.349b	-	0.428a	-	0.134c
P_1	1.94a	0.306b	-	0.457a	-	0.096c
P_2	1.52a	0.213b	-	0.382a	-	0.087c
P_3	1.42a	0.136b	-	0.627a	-	0.067c
P_4	1.85a	0.316b	-	0.516a	-	0.220b

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 15. Average flow-weighted concentrations of PO_4-P in subsurface drainage.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	---------- mg/L ----------					
P_O	0.085b	0.085b	-	0.059c	-	0.821a
P_1	0.293a	0.237b	-	0.208b	-	1.177a
P_2	2.118a	1.733b	-	0.497c	-	1.785a
P_3	3.770a	2.237b	-	0.50d	-	1.666c
P_4	3.557a	3.717a	-	2.500b	-	3.316a

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 16. Average loss of PO_4-P with subsurface drainage.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	---------- kg/ha ----------					
P_O	0.015a	0.003c	-	0.002c	-	0.011b
P_1	0.056a	0.007c	-	0.009c	-	0.011b
P_2	0.321a	0.036b	-	0.018c	-	0.016c
P_3	0.546a	0.030b	-	0.034b	-	0.011b
P_4	0.658a	0.117b	-	0.127a	-	0.072b

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 17. Average flow-weighted concentrations of total P in subsurface drainage.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	---------- mg/L ----------					
P_O	0.343b	0.419b	-	0.220c	-	23.36a
P_1	0.707a	0.519b	-	0.425b	-	24.8a
P_2	3.324b	2.956c	-	14.61b	-	27.23a
P_3	36.8a	26.30b	-	26.64b	-	33.95a
P_4	49.34b	74.91a	-	32.06b	-	36.2b

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 18. Average loss of total P with subsurface drainage.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	---------- kg/ha ----------					
P_O	0.061a	0.015c	-	0.009d	-	0.313b
P_1	0.137b	0.016c	-	0.018c	-	0.238b
P_2	0.505c	0.062d	-	0.555b	-	0.238c
P_3	5.336a	0.353b	-	1.651a	-	0.227b
P_4	9.127a	0.591b	-	1.635a	-	0.796b

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 19. Average flow weighted concentrations of sediment in subsurface drainage.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	---------- mg/L ----------					
P_O	3218b	3880a	-	3720a	-	1546b
P_1	2275b	3773a	-	4139a	-	1545b
P_2	3867b	1308c	-	3791b	-	2424a
P_3	3662a	1288b	-	188d	-	709c
P_4	1939a	1004c	-	5377a	-	2791b

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 20. Average loss of sediment with subsurface drainage.

	Nicollet		Marshall		Fayette	
P Trt	WC	WOC	WC	WOC	WC	WOC
	kg/ha					
P_O	573a	135b	-	112c	-	21d
P_1	441a	115b	-	182a	-	15c
P_2	588a	28b	-	144a	-	21b
P_3	5802a	17b	-	12c	-	5d
P_4	359a	32c	-	274a	-	61b

*Means with the same letter across rows for each variable are not significantly different at significance level of P = 0.05; comparisons are to be made between WC and WOC for the Nicollet soil and between WOC for the three soils.

Table 21. Comparison of P concentrations in surface runoff versus available P parameters.

Source	PO_4-P		Total-P	
	Intercept	Slope	Intercept	Slope
Nicollet (w/o)	0.047	0.0023	1.646	0.005
Nicollet (w/s)	0.038	0.0016	0.889	0.0028
Marshall	0.087	0.0022	2.212	0.0083
Fayette	0.045	0.0028	1.298	0.0065

W/O = without screen, W/S = with screen

Table 22 . Soil properties and P additions.

Soil Type	P add ppm	Bray P-1 ppm	pH	K ppm	Ca ppm	Mg ppm	Total C %	Total-P ppm	P Increase ppm	P Recovery %
Nicolett	0	14.9	6.0	202	3332	415	2.77	437		
Nicolett	50	50.6	6.0	-	-	-	-	-	36	71
Nicolett	125	101.2	5.8	-	-	-	-	-	86	69
Nicolett	300	251.5	5.5	-	-	-	-	-	237	79
Nicolett	600	478.4	5.3	-	-	-	-	-	463	77
Marshall	0	23.6	7.1	397	3282	355	2.35	515		
Marshall	50	56.6	6.9	-	-	-	-	-	33	66
Marshall	125	110.2	6.5	-	-	-	-	-	87	69
Marshall	300	273.7	5.9	-	-	-	-	-	250	83
Marshall	600	474.9	5.4	-	-	-	-	-	451	75
Fayette	0	7.5	6.3	123	1887	608	1.31	374		
Fayette	50	29.8	6.0	-	-	-	-	-	22	45
Fayette	125	88.8	5.7	-	-	-	-	-	81	65
Fayette	300	181.4	5.4	-	-	-	-	-	174	58
Fayette	600	482.8	5.2	-	-	-	-	-	475	79

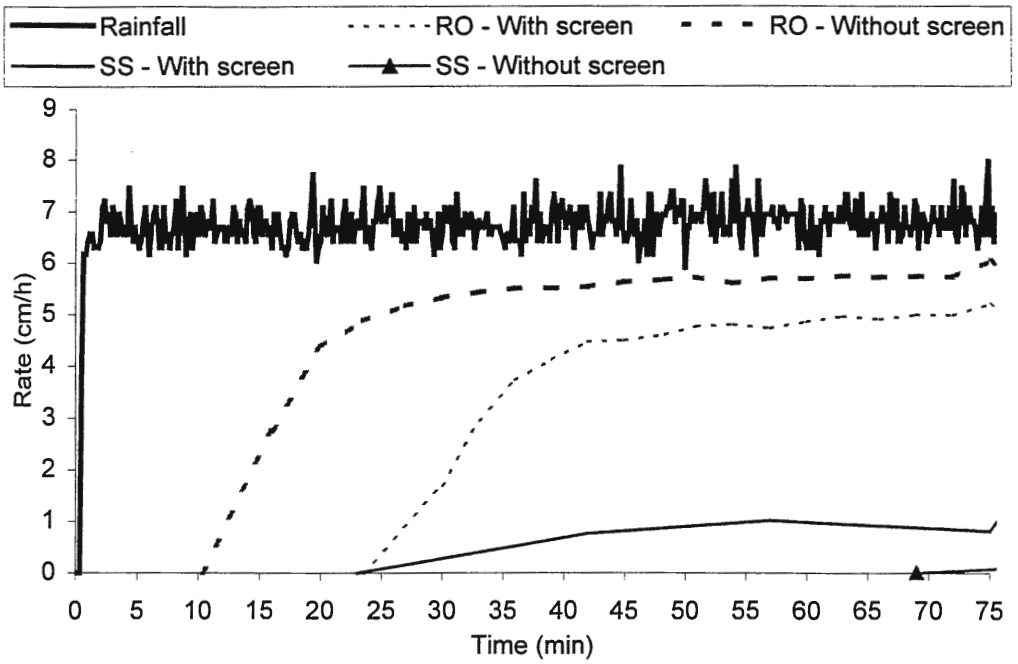

Figure 3. Effect of screen on surface runoff (RO) and subsurface drainage (SS) rates for Nicollet soil (vacuum applied at 25 min after rainfall started, off at 74 min).

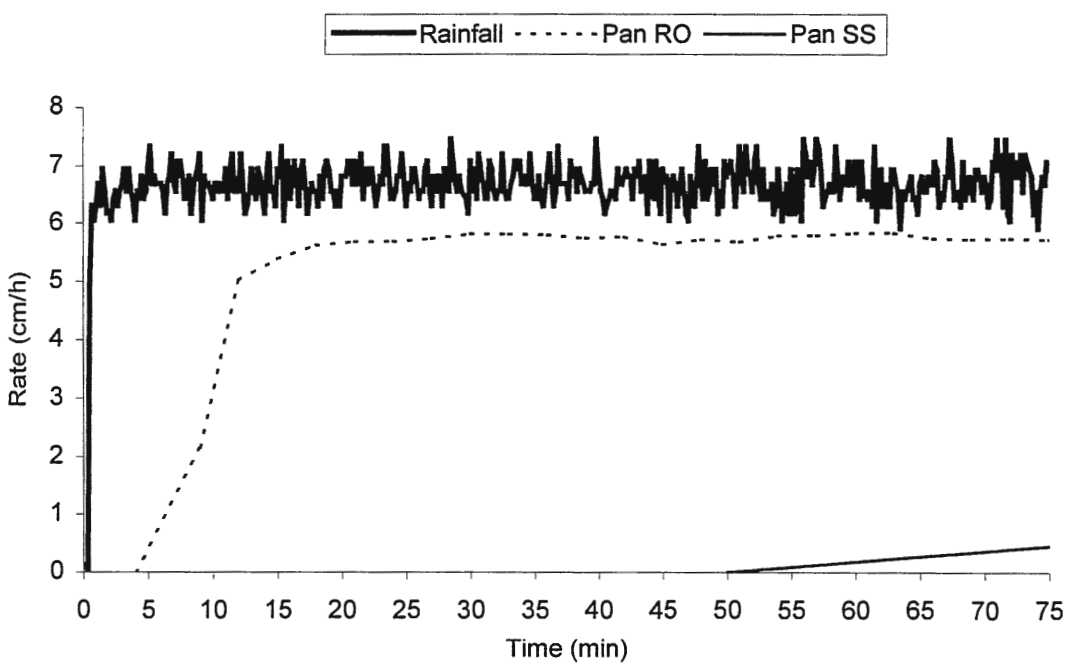

Figure 4. Surface runoff (SR) and subsurface drainage (SS) rates for Marshall soil (vacuum applied at 50 min after rainfall started, off at 74 min).

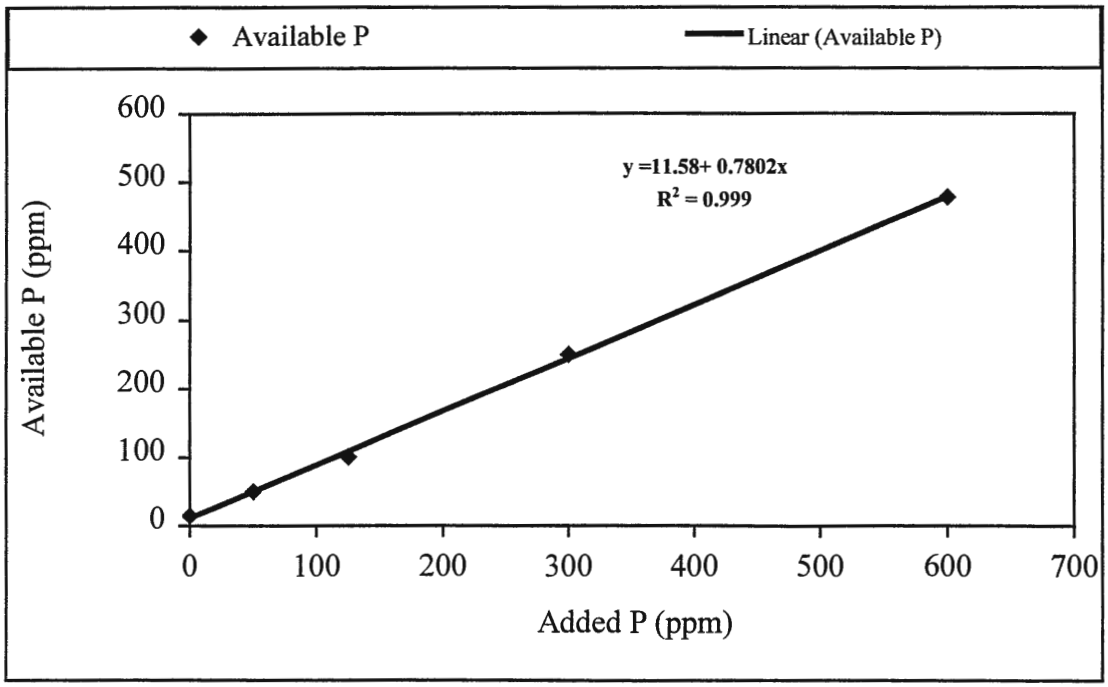

Figure 5. Available P versus added P for Nicollet soil.

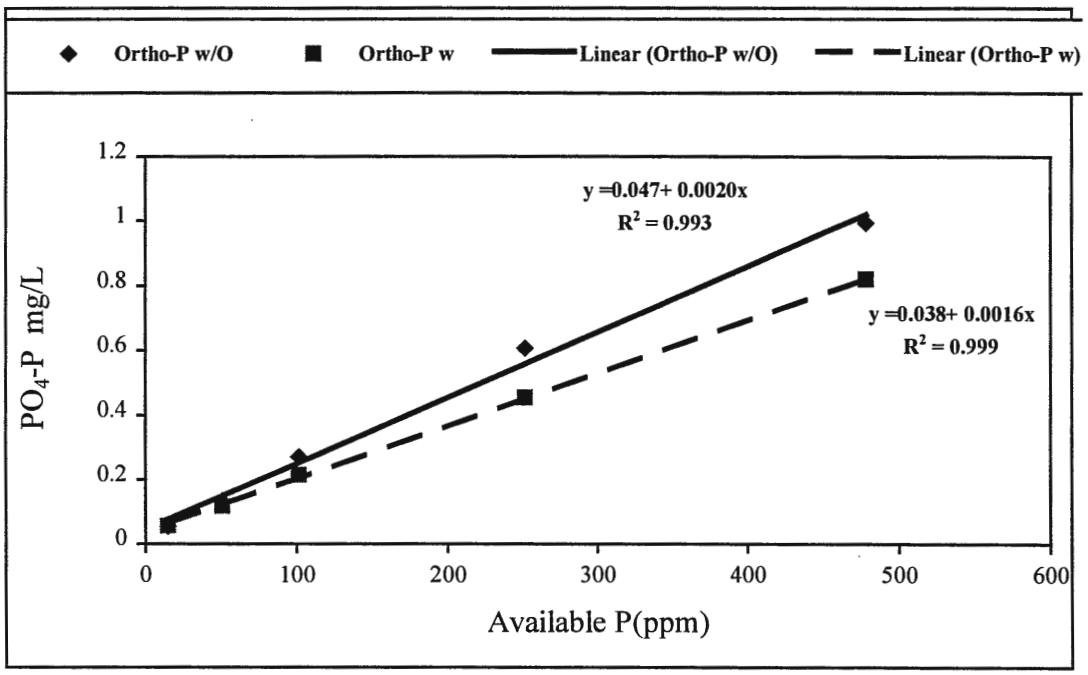

Figure 6. PO_4-P in surface runoff versus available P with and without screen for Nicollet soil.

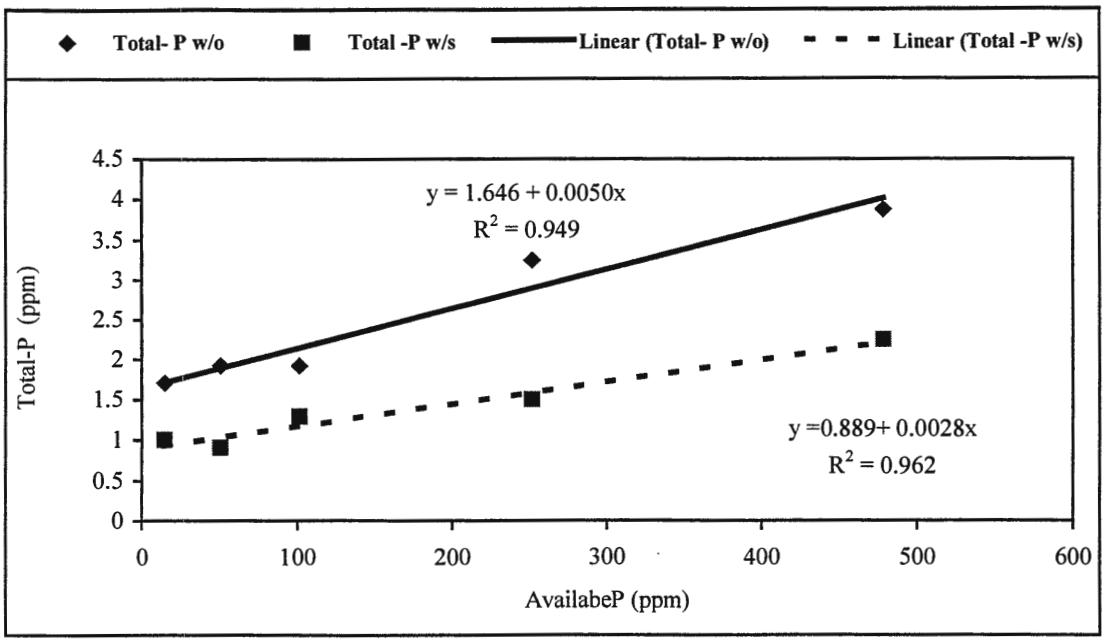

Figure 7. Total-P in surface runoff versus available P with and without screen for Nicollet soil.

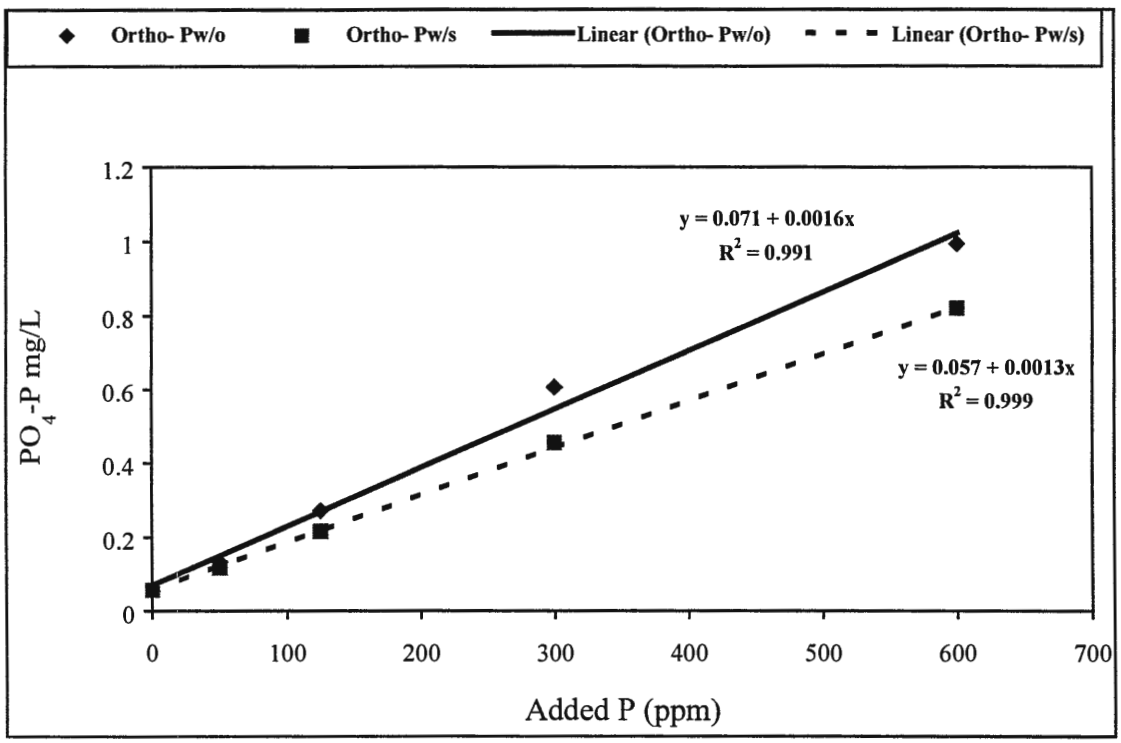

Figure 8. PO_4-P in surface runoff versus added P with and without screen for Nicollet soil.

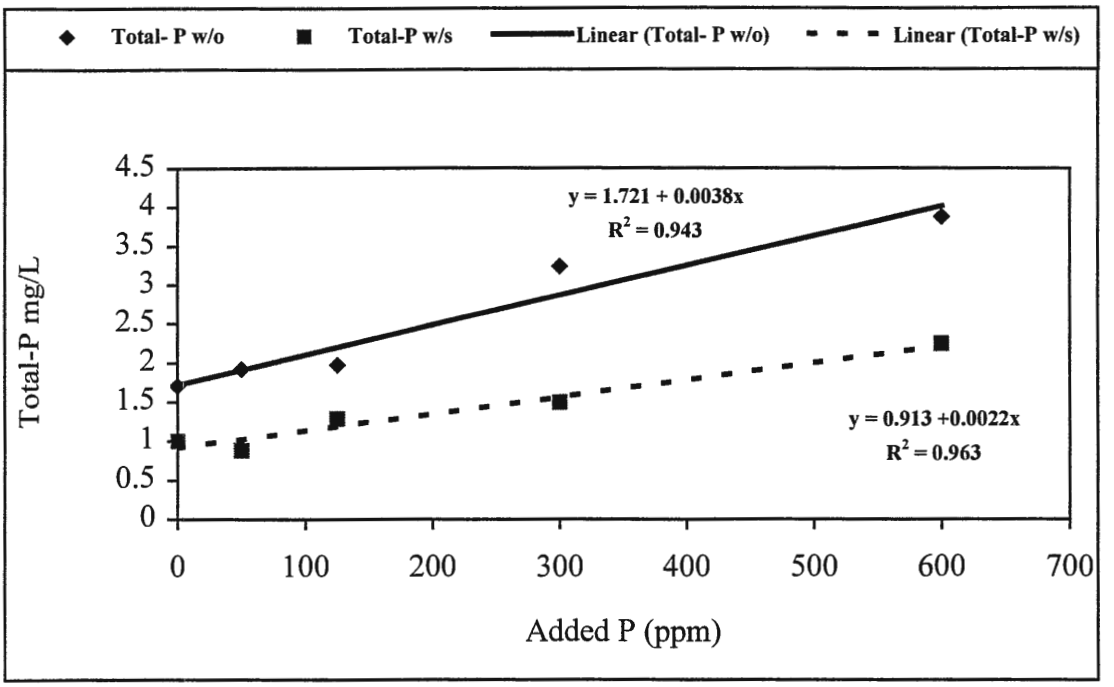

Figure 9. Total-P in surface runoff versus added P with and without screen for Nicollet soil.

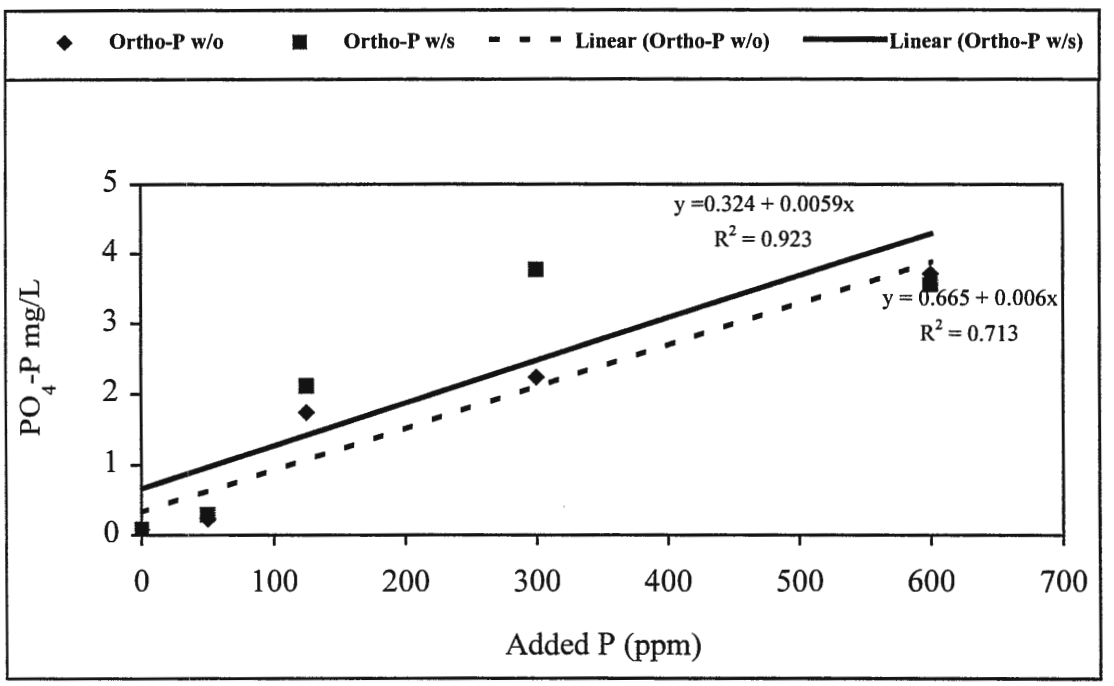

Figure 10. PO_4-P in subsurface drainage versus added P with and without screen for Nicollet soil.

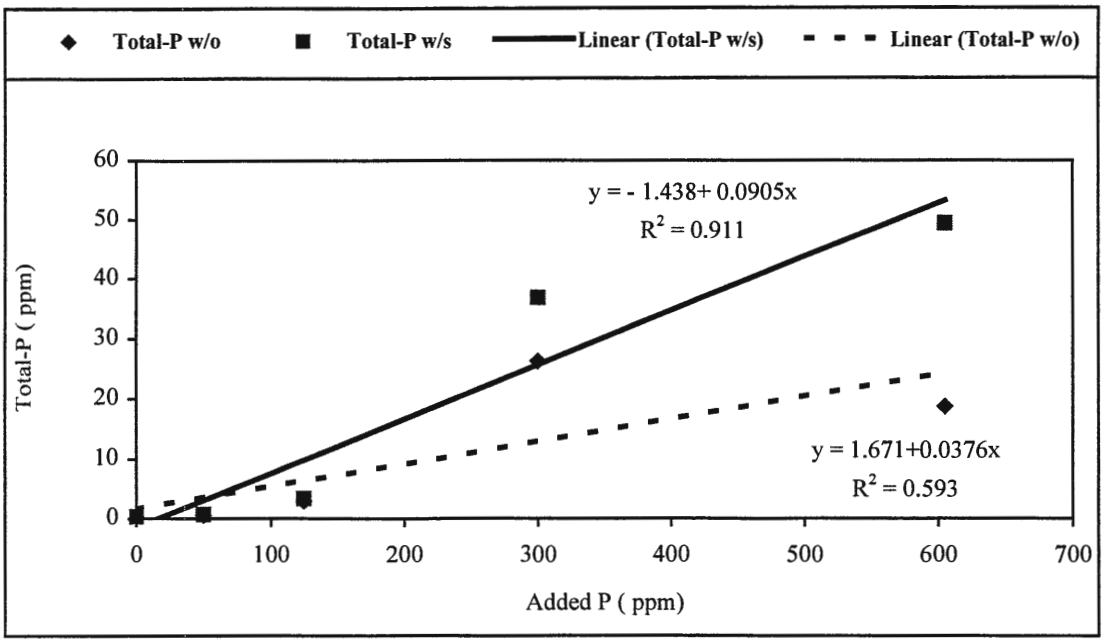

Figure 11. Total-P in subsurface drainage versus added P, with and without screen for Nicollet soil.

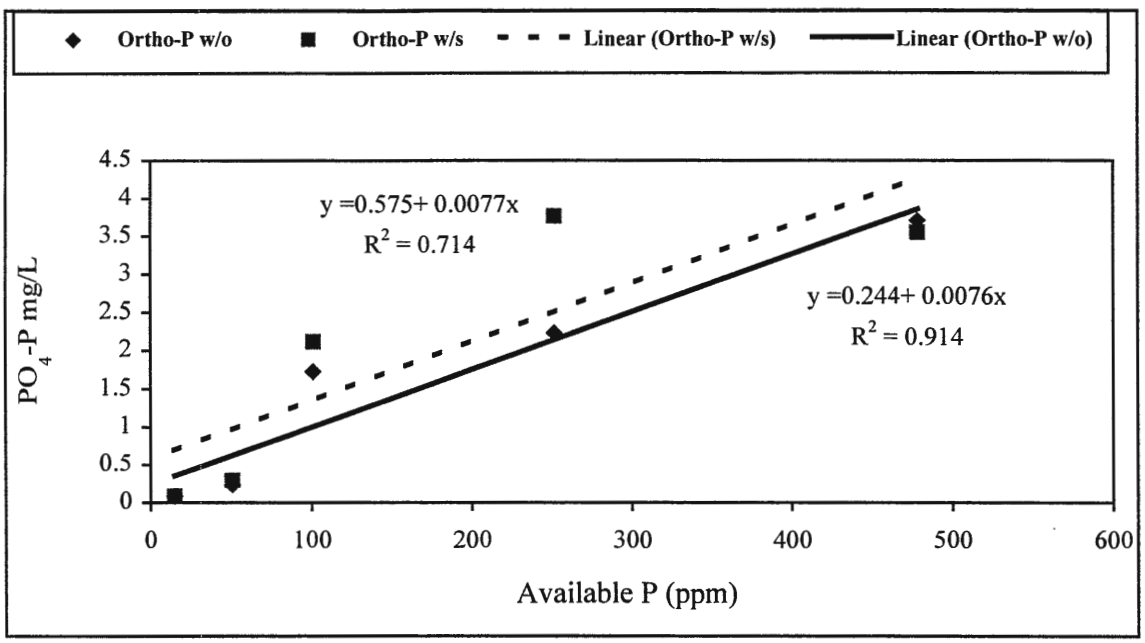

Figure 12. PO_4-P in subsurface drainage versus available P with and without screen for Nicollet soil.

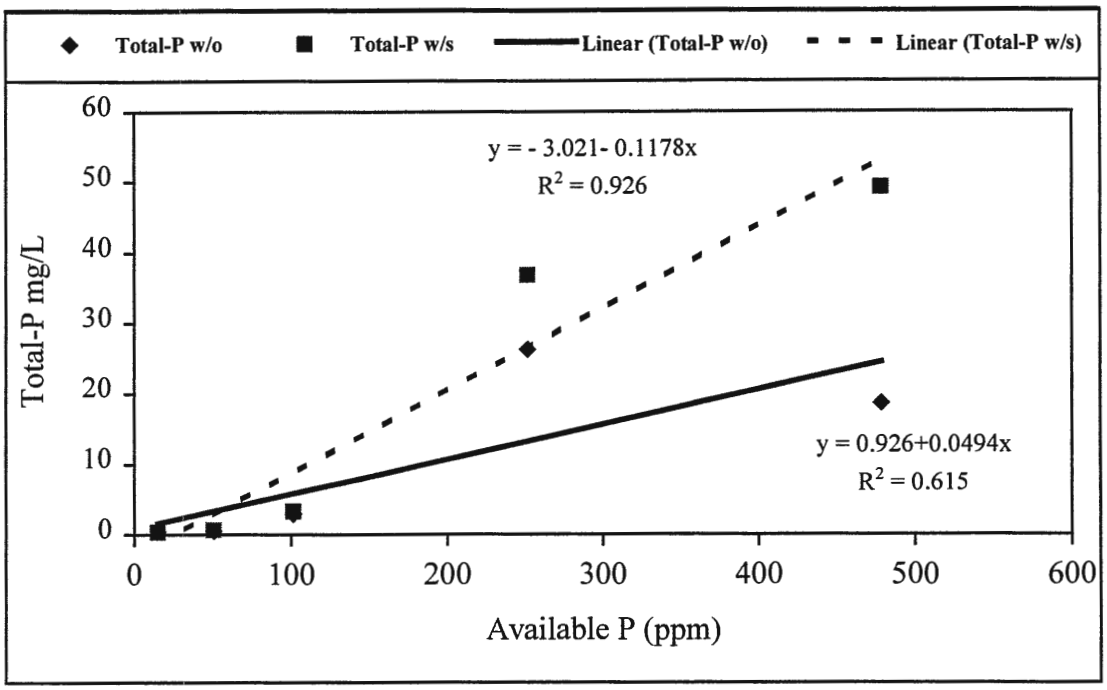

Figure 13. Total-P in subsurface drainage versus added P, with and without screen for Nicollet soil.

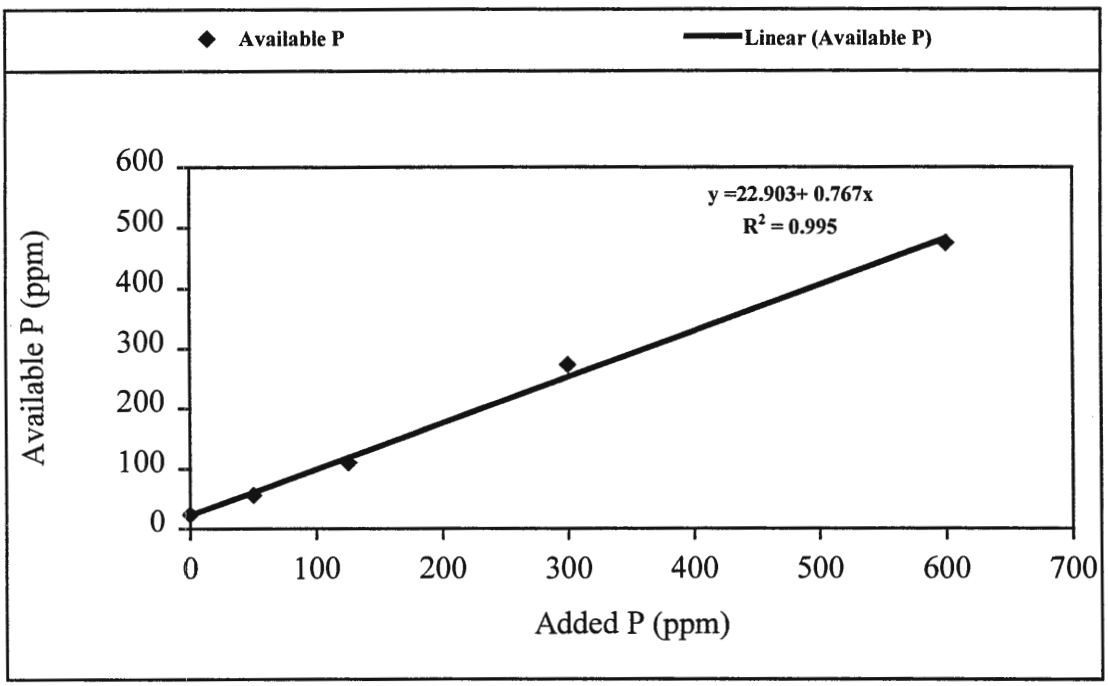

Figure14. Available P versus added P for Marshall soil.

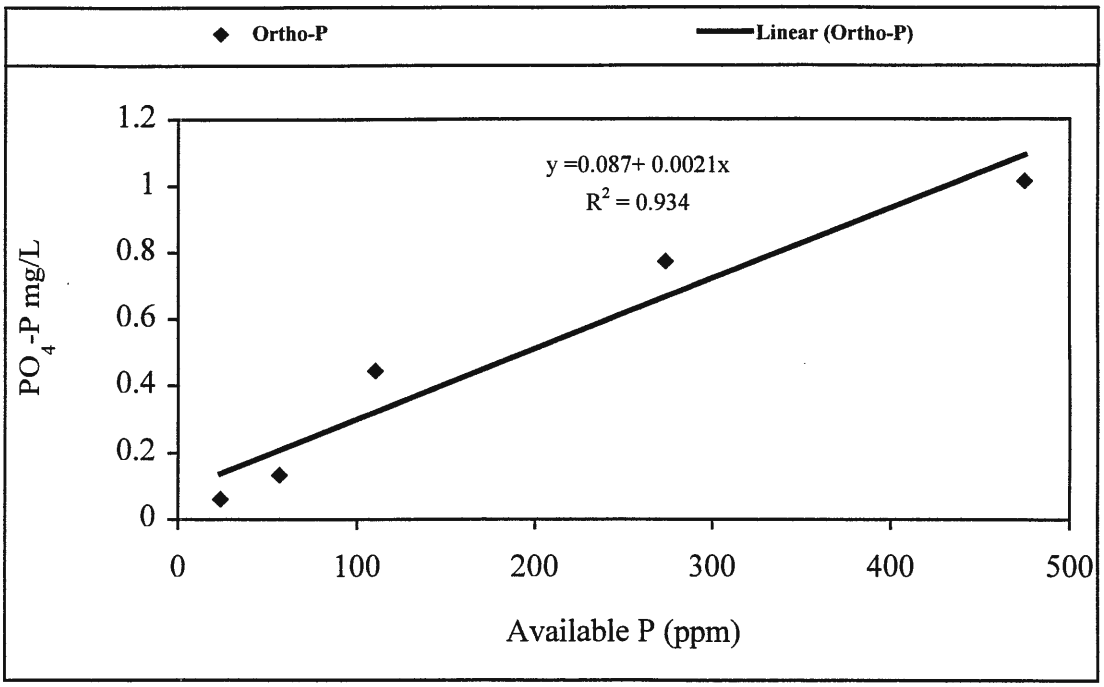

Figure 15. PO_4-P in surface runoff versus available P for Marshall soil.

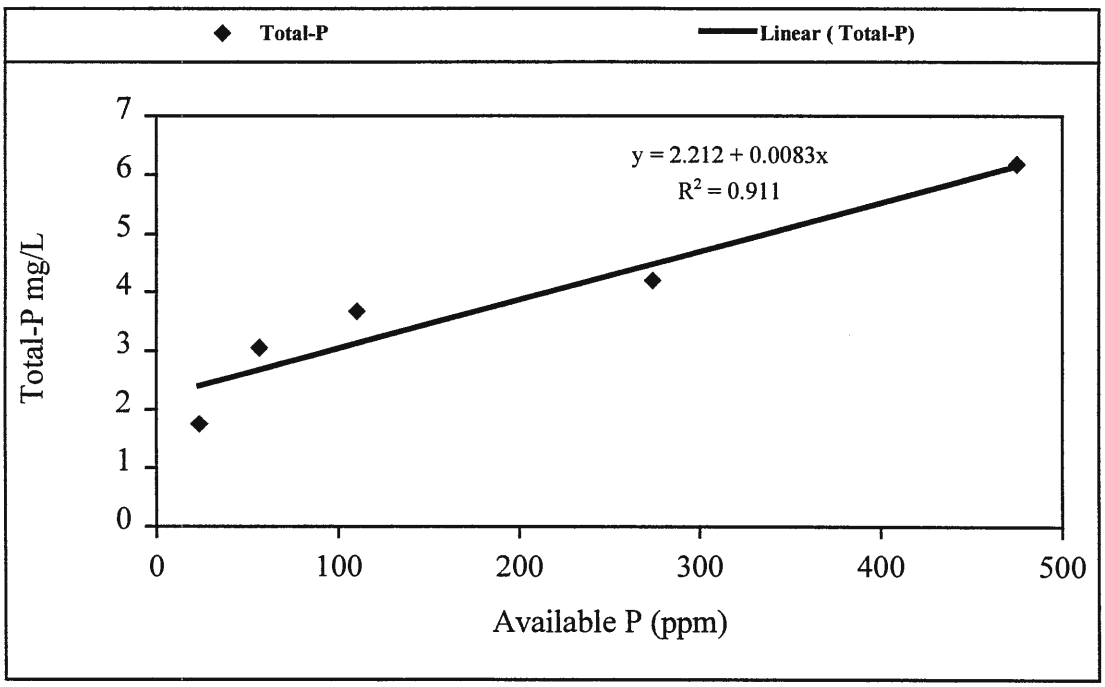

Figure 16. Total-P in surface runoff versus available P for Marshall soil.

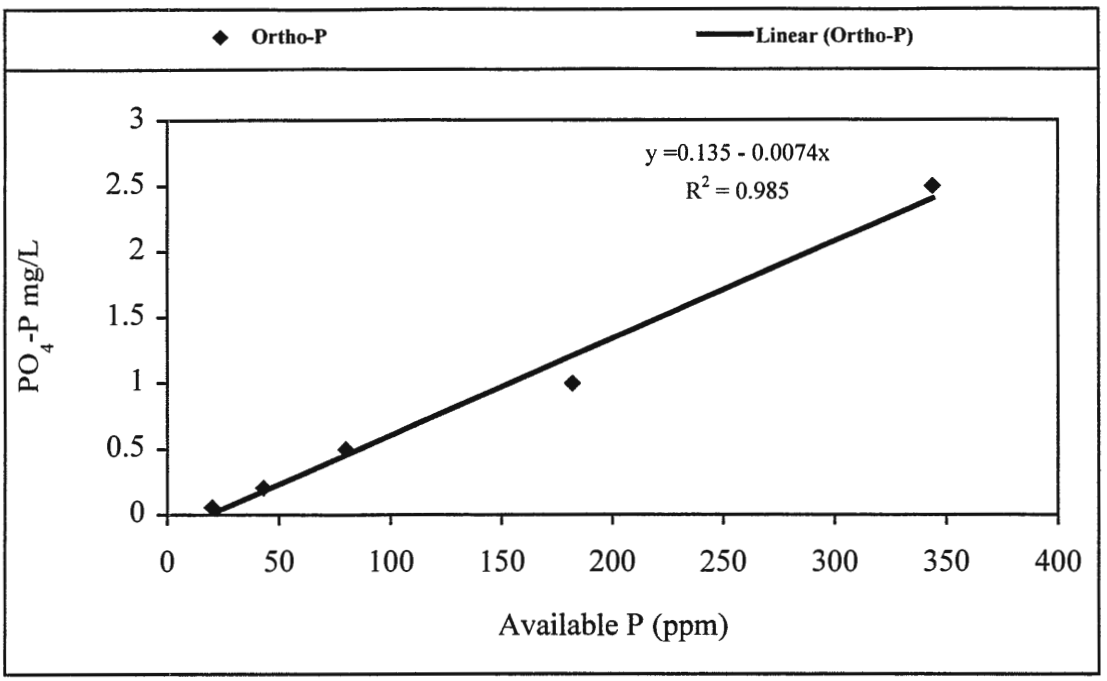

Figure 17. PO_4-P in subsurface drainage versus available P for Marshall soil.

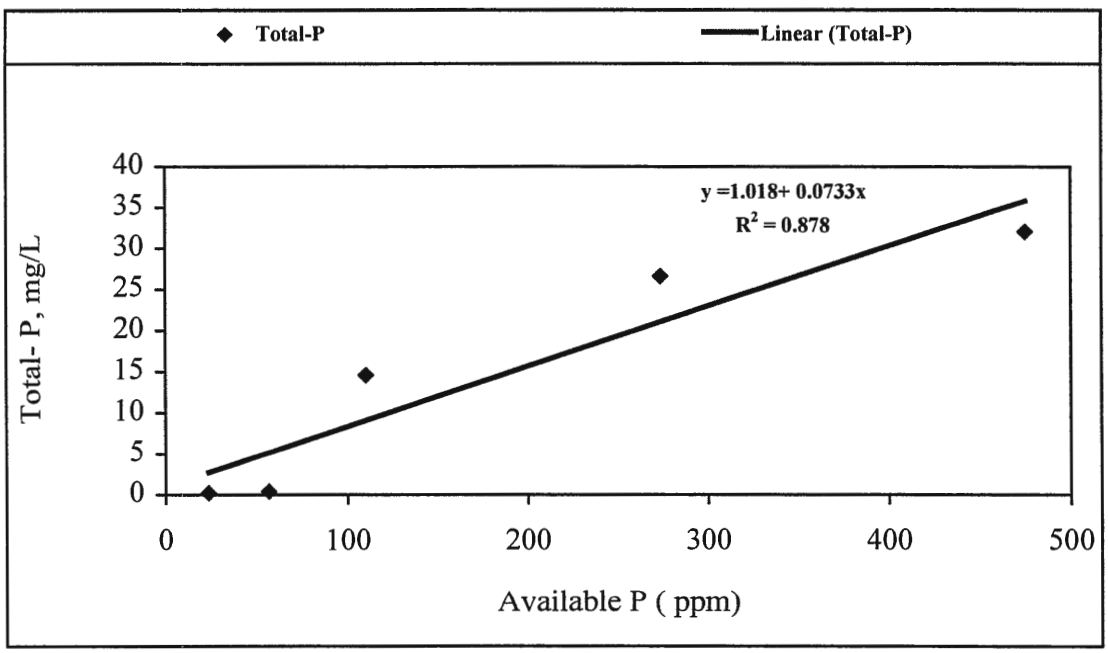

Figure18. Total-P in subsurface drainage versus available P for Marshall soil.

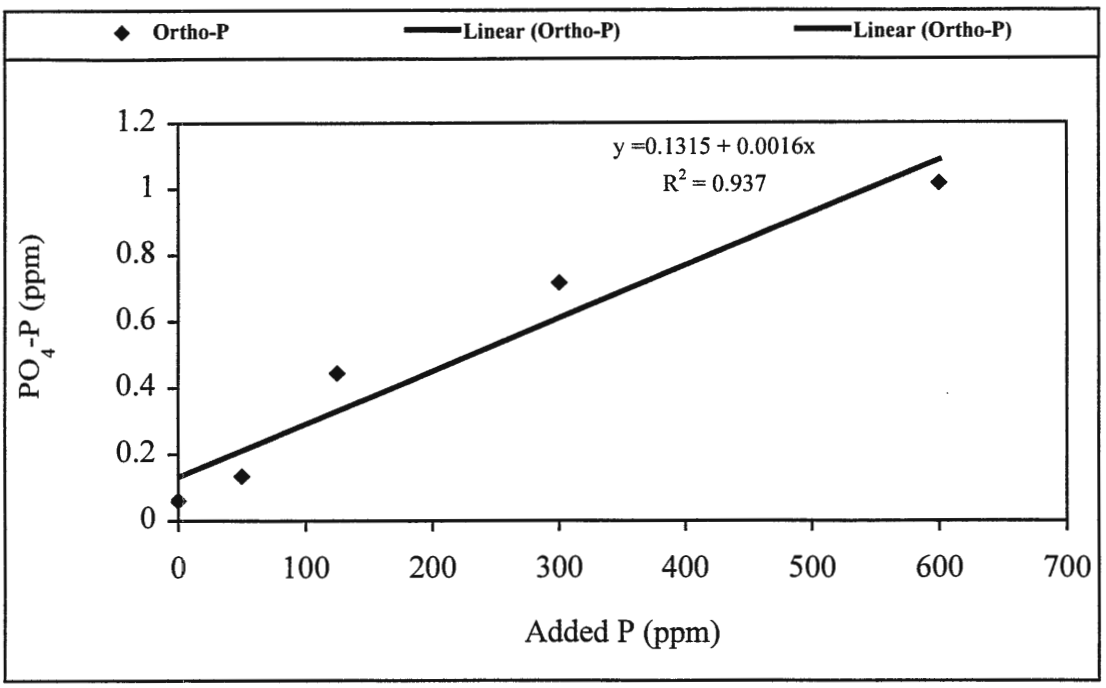

Figure 19. PO_4-P versus added P for Marshall soil.

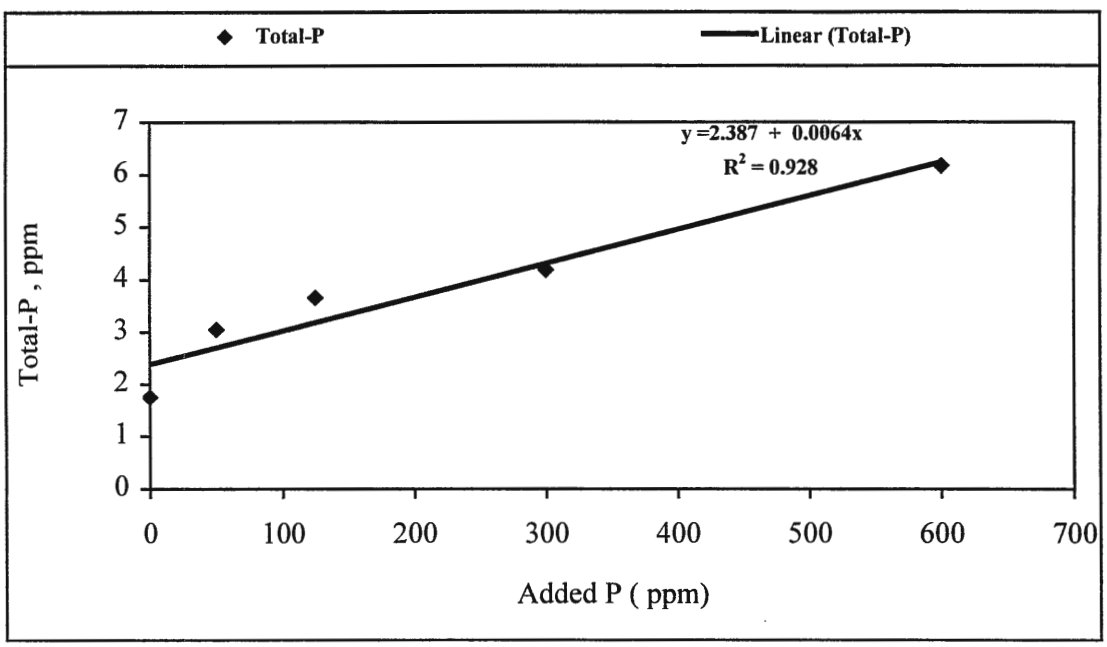

Figure 20. Total-P versus added P for Marshall soil.

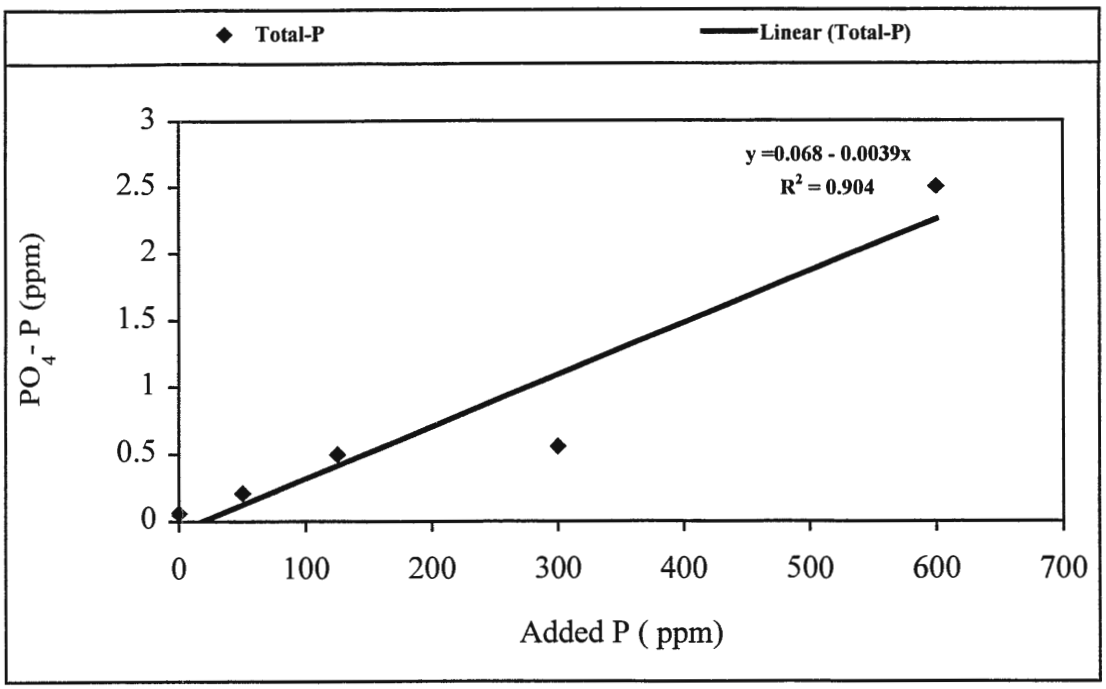

Figure 21. PO_4-P in subsurface drainage versus added P for Marshall soil.

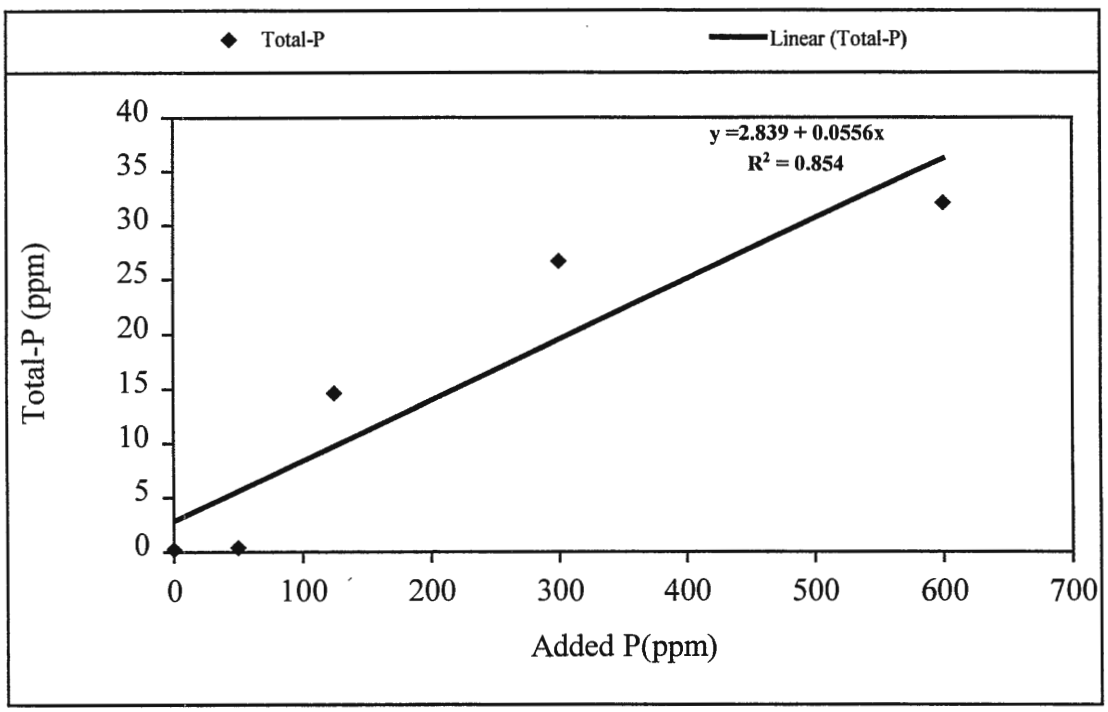

Figure 22. Total-P in subsurface drainage versus added P for Marshall soil.

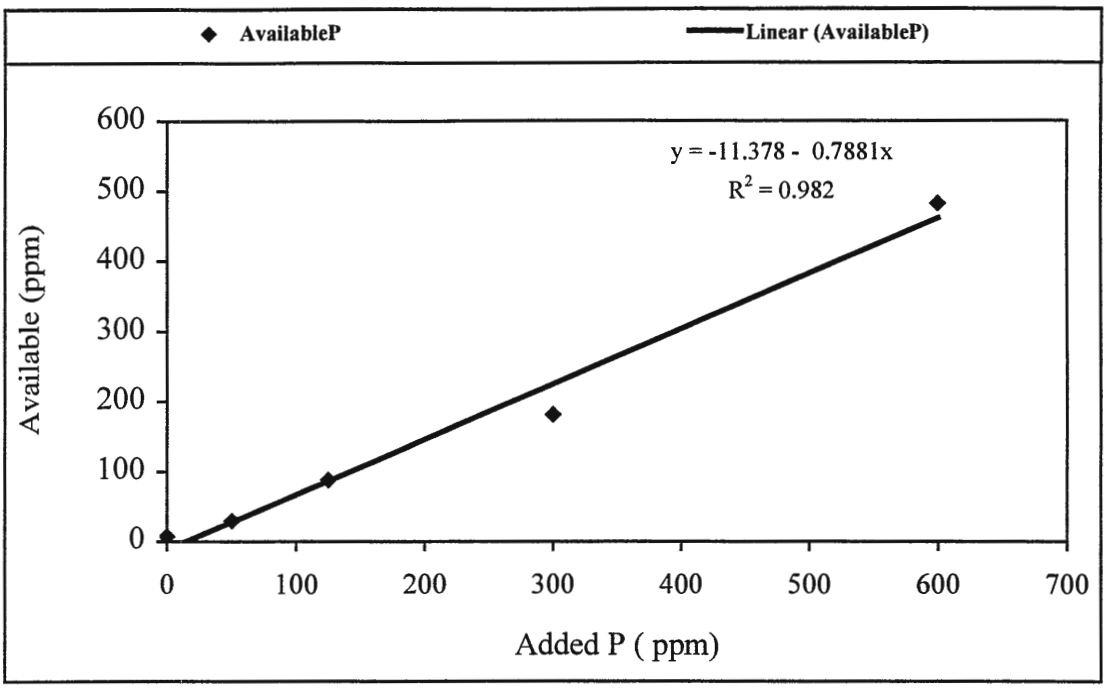

Figure 23. Available P versus added P for Fayette soil.

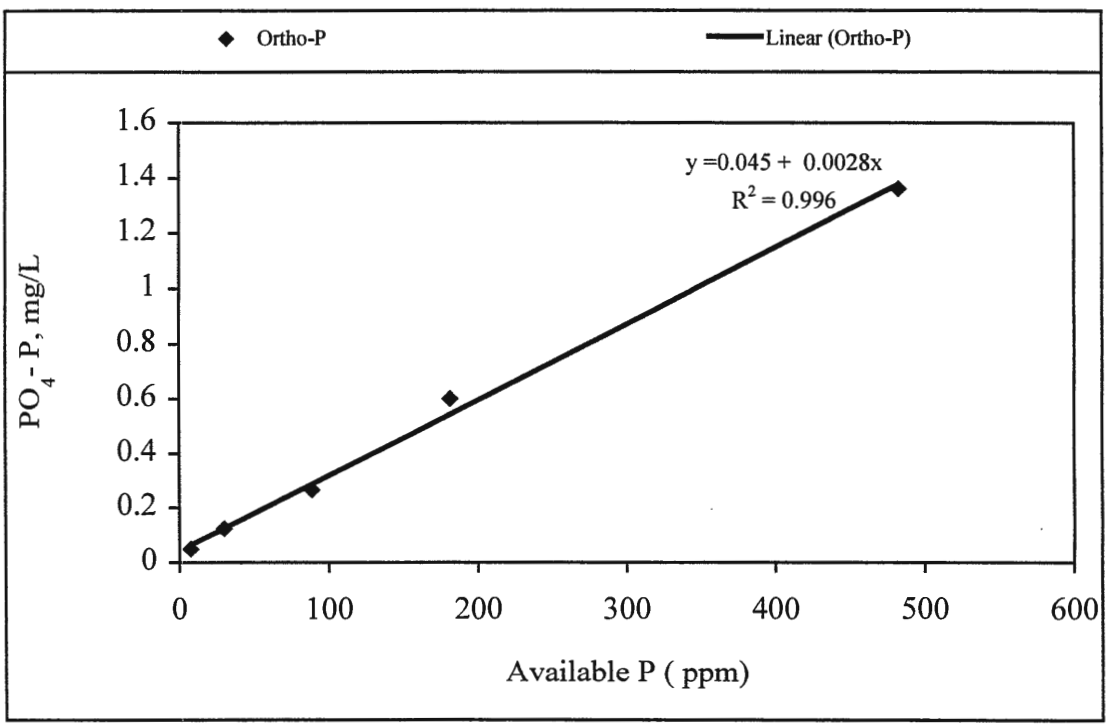

Figure 24. PO_4-P in surface runoff versus available P for Fayette soil.

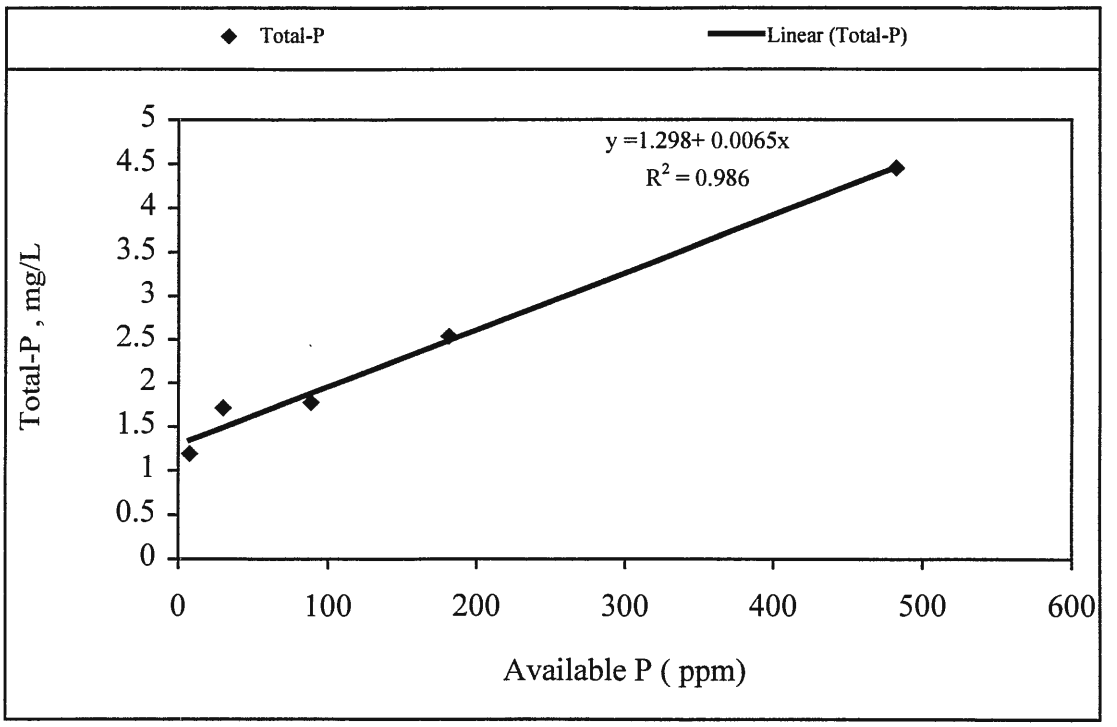

Figure 25. Total-P in surface runoff versus available P for Fayette soil.

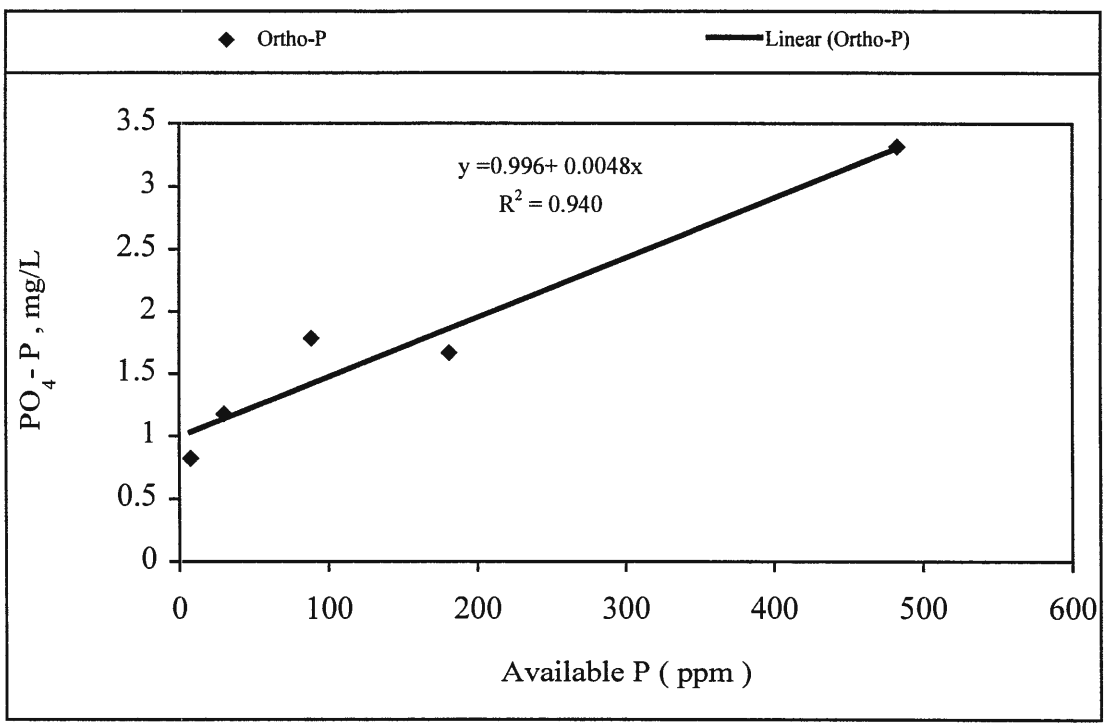

Figure 26. Total-P in subsurface drainage versus added P for Fayette soil.

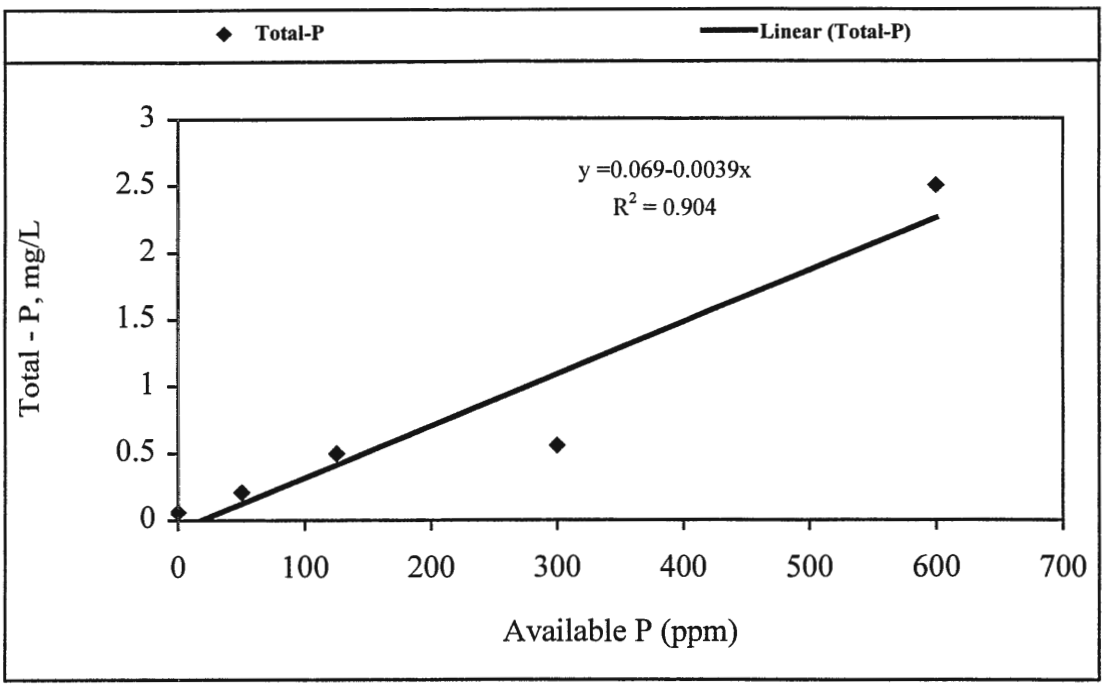

Figure 27. Total-P in subsurface drainage versus available P for Fayette soil.

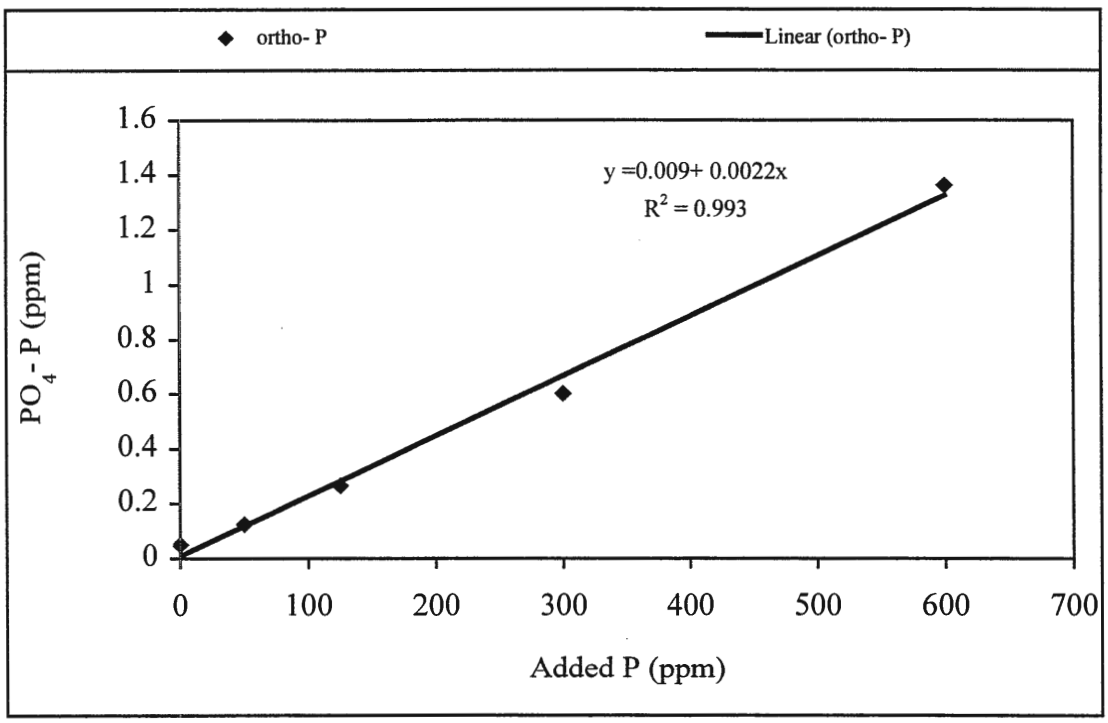

Figure 28. PO_4-P in surface runoff versus added P for Fayette soil.

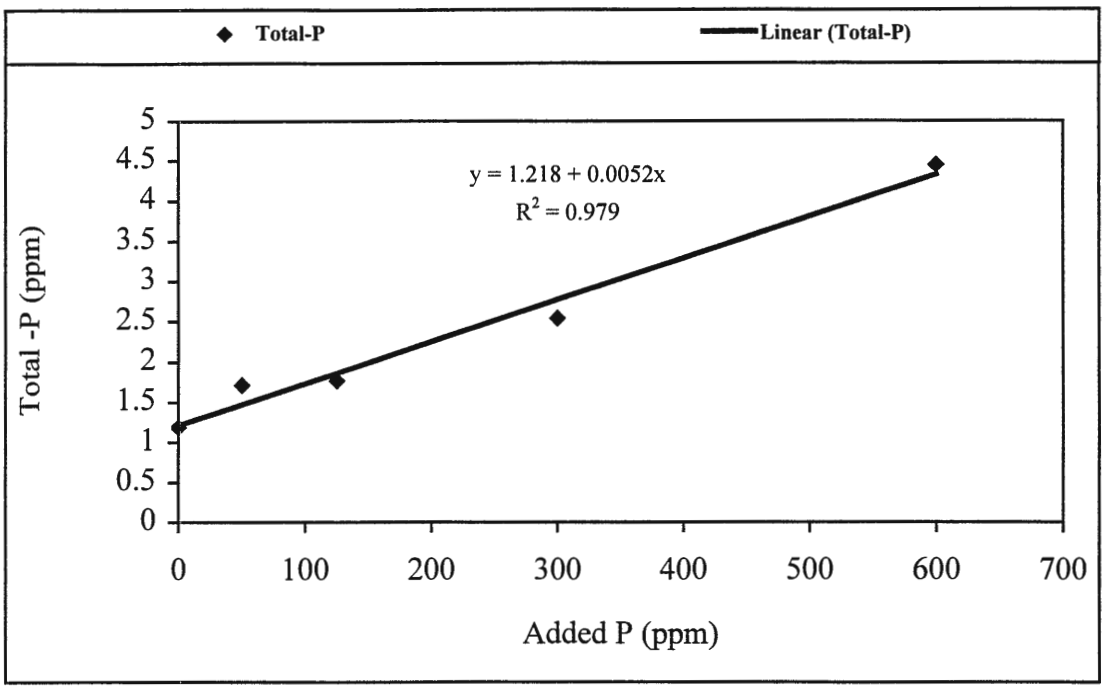

Figure 29. Total-P in surface runoff versus added P for Fayette soil.

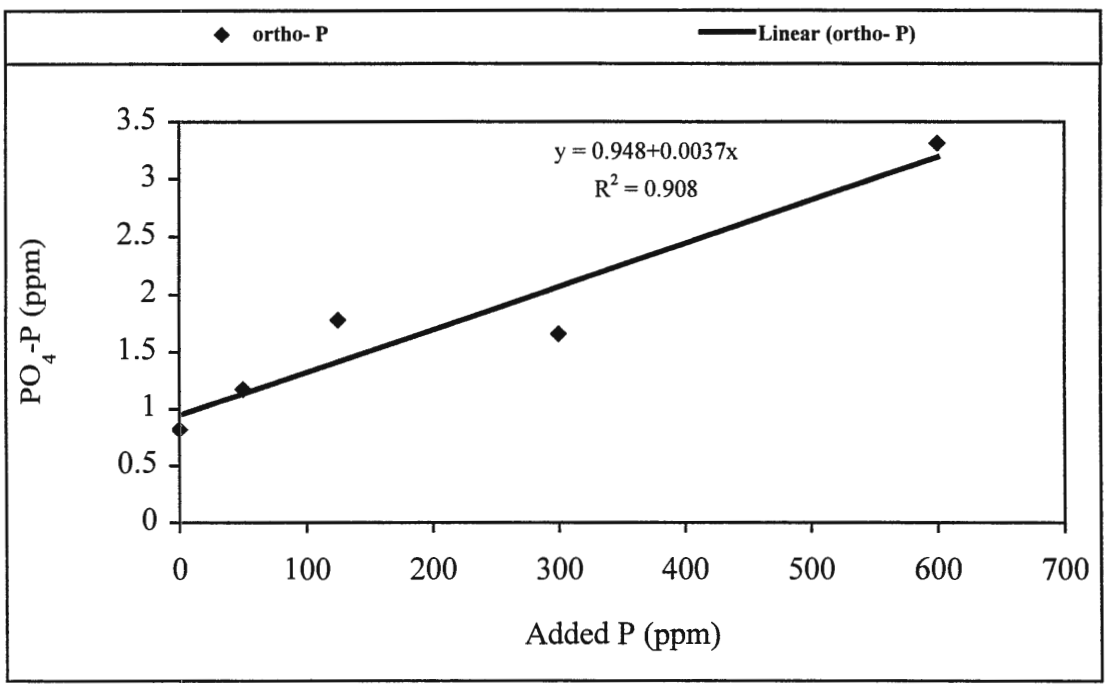

Figure 30. PO_4-P in subsurface drainage versus added P for Fayette soil.

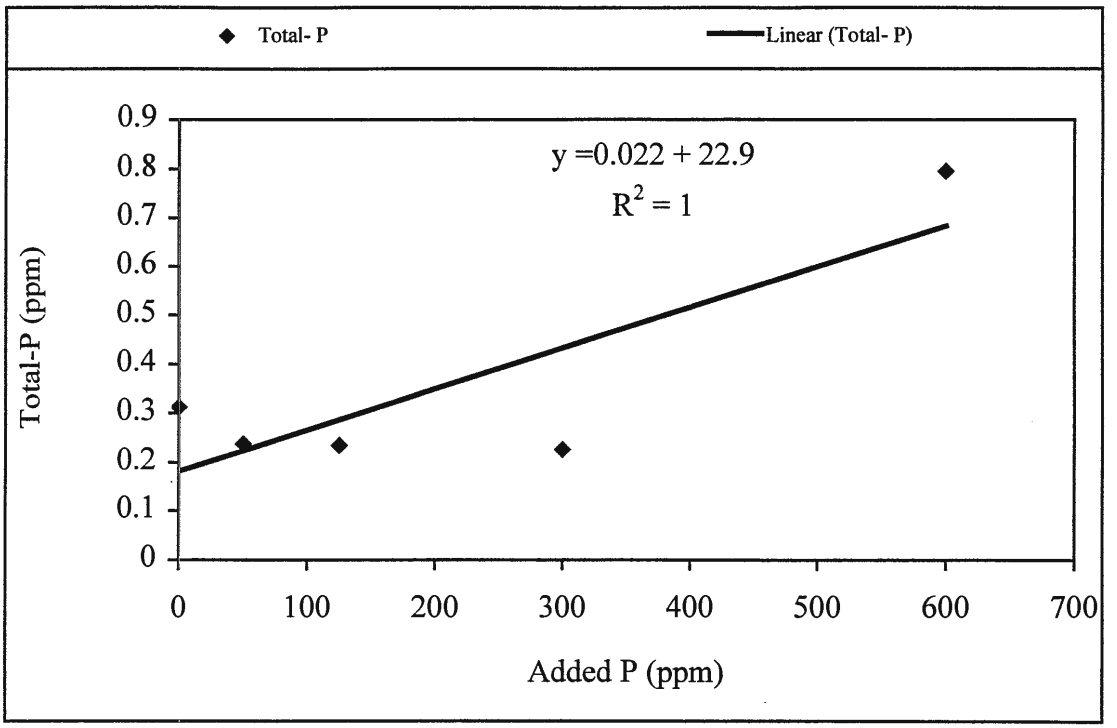

Figure 31. Total-P versus added P for Fayette soil.

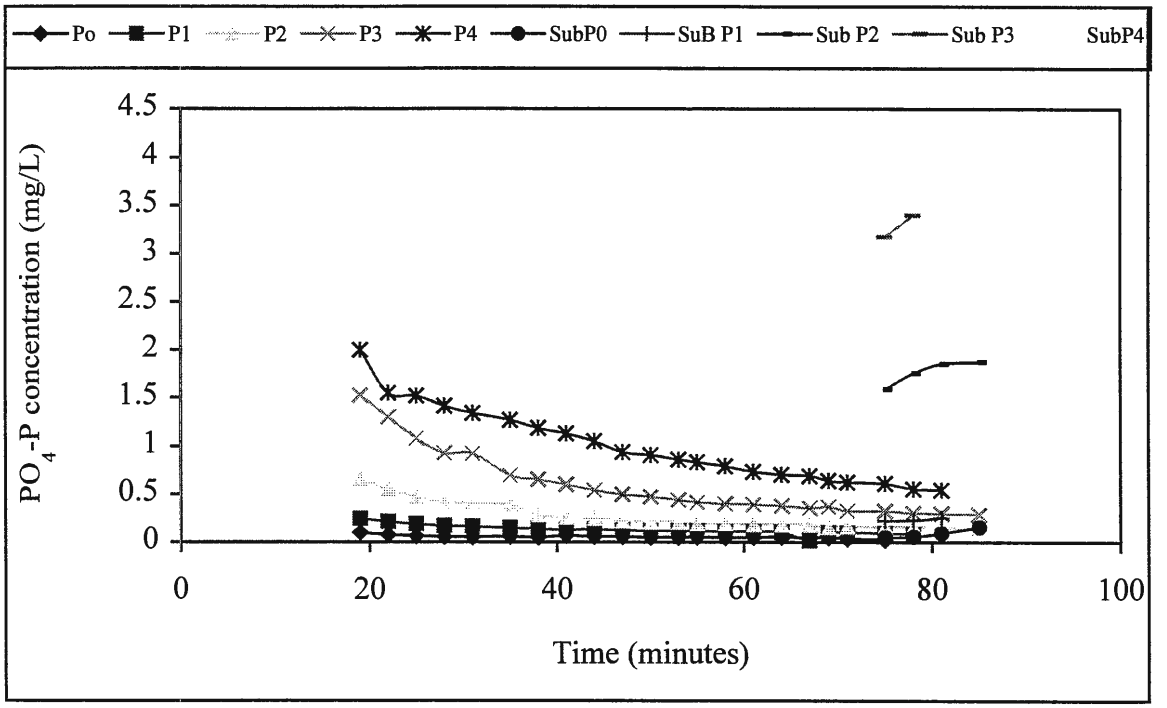

Figure 32. Average flow-weighted concentrations of PO_4-P in runoff and subsurface drainage water from Nicollet soil without screen.

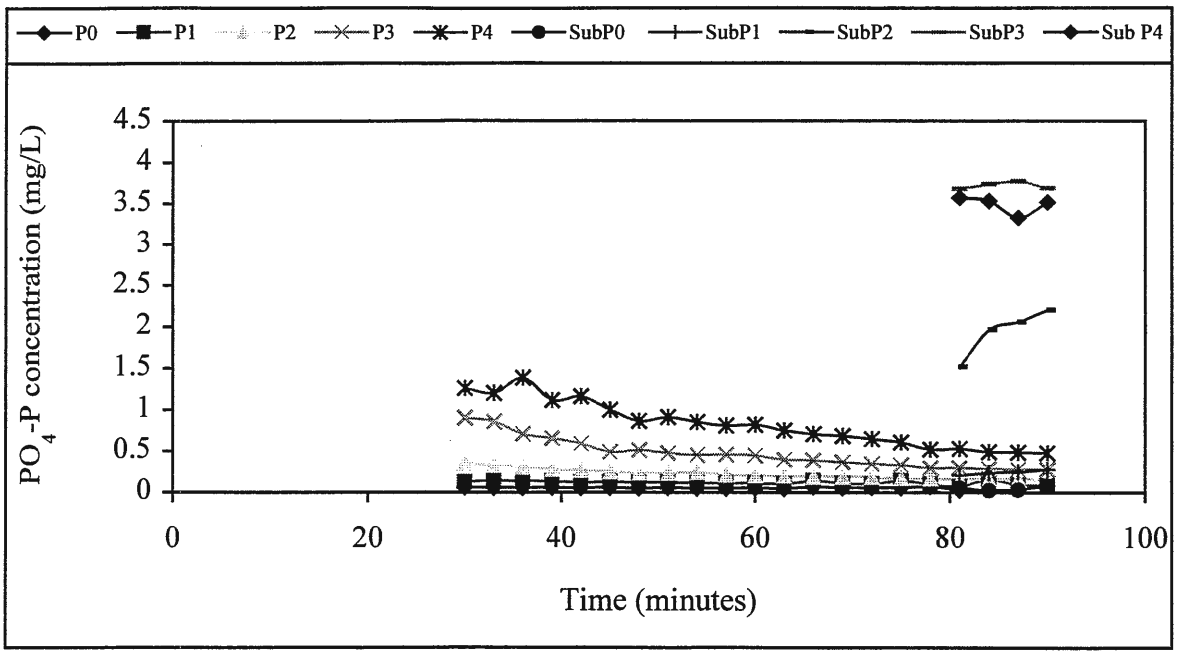

Figure 33. Average flow-weighted concentrations of PO_4-P in runoff and subsurface drainage water from Nicollet soil with screen.

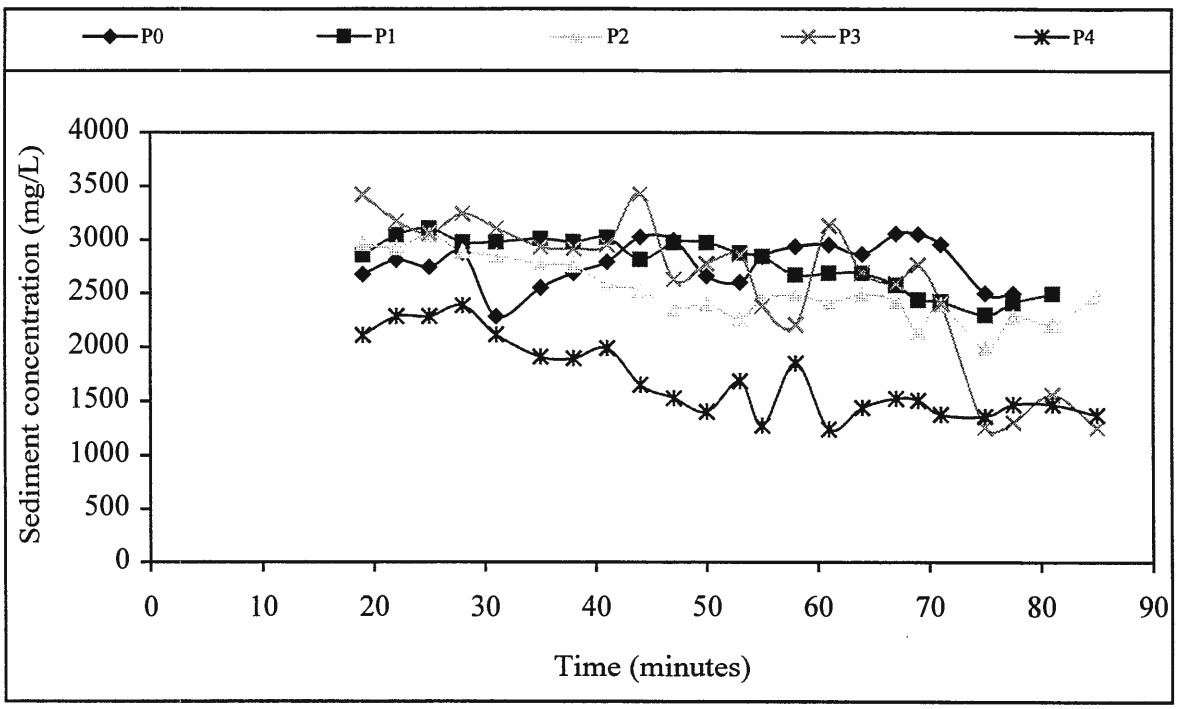

Figure 34. Average flow-weighted concentrations of sediment in runoff and subsurface drainage water from Nicollet soil without screen.

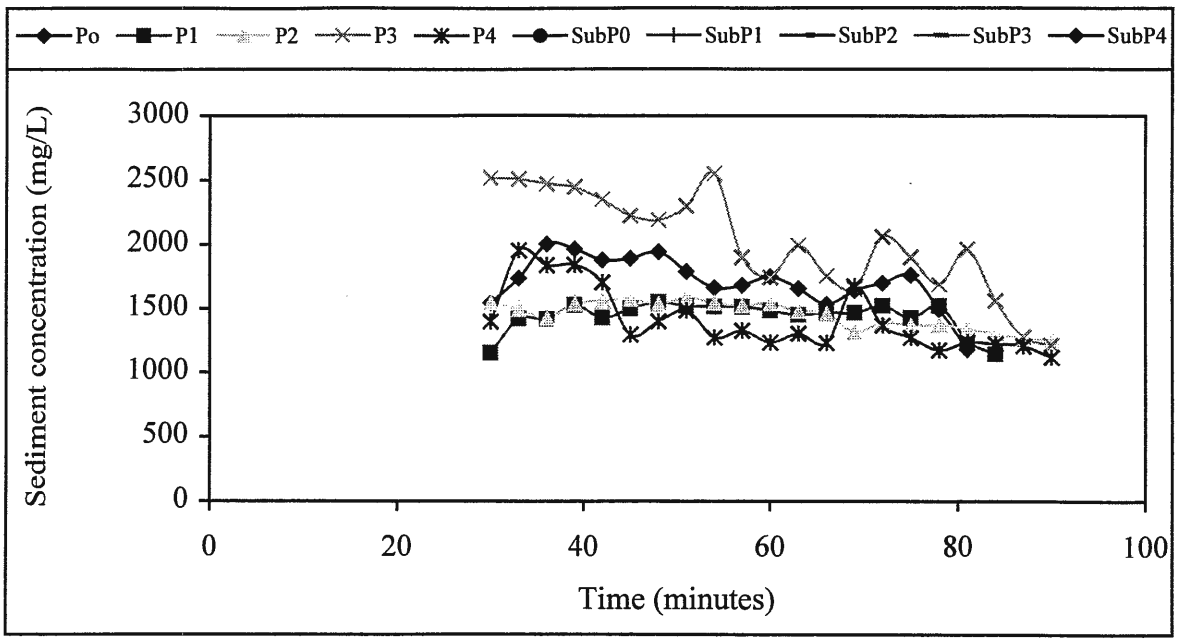

Figure 35. Average flow-weighted concentrations of sediment in runoff and subsurface drainage water from Nicollet soil with screen.

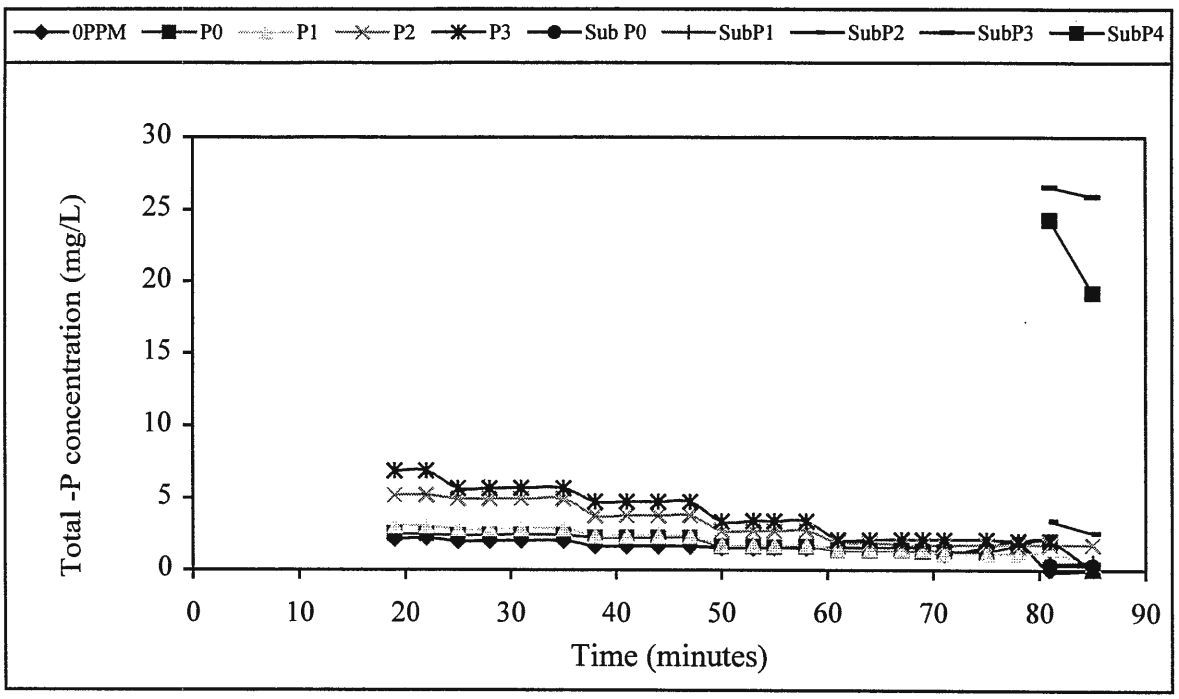

Figure 36. Average flow-weighted concentrations of total-P in runoff and subsurface drainage water from Nicollet soil without screen

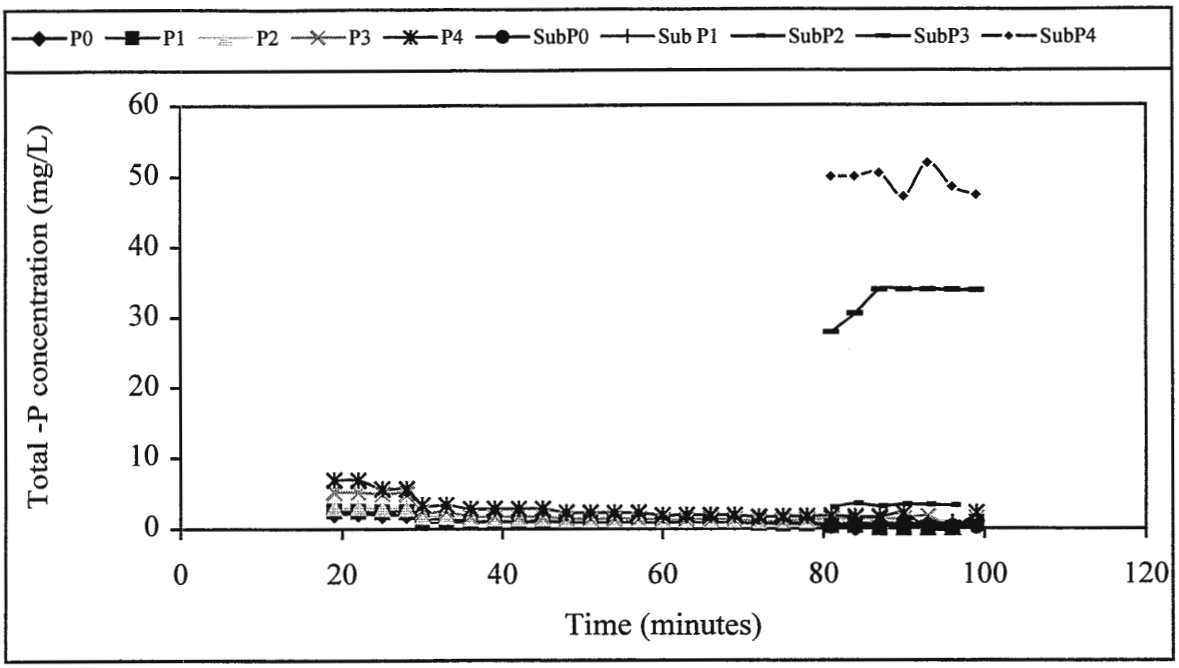

Figure 37. Average flow-weighted concentrations of total -P in runoff and subsurface drainage water from Nicollet soil with screen.

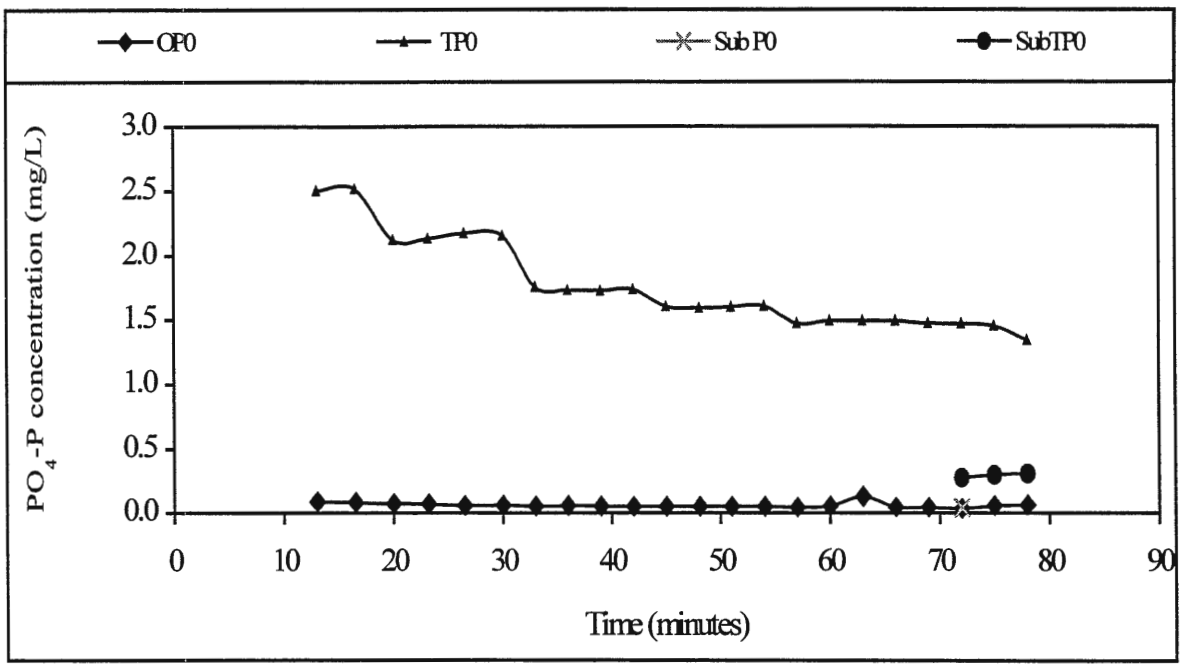

Figure 38. Average flow-weighted concentration of PO_4-P and total-P in runoff and subsurface drainage water from Marshall soil without screen.

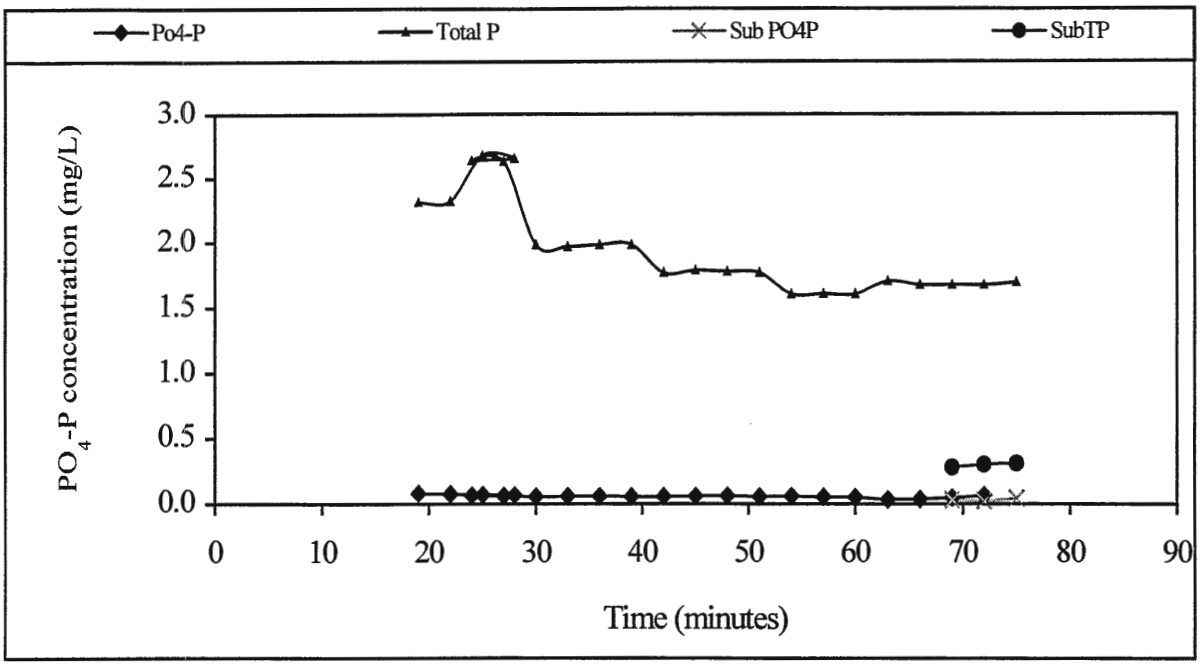

Figure 39. Average flow-weighted concentrations of PO_4-P and total-P in runoff and subsurface drainage water from Marshall soil with screen.

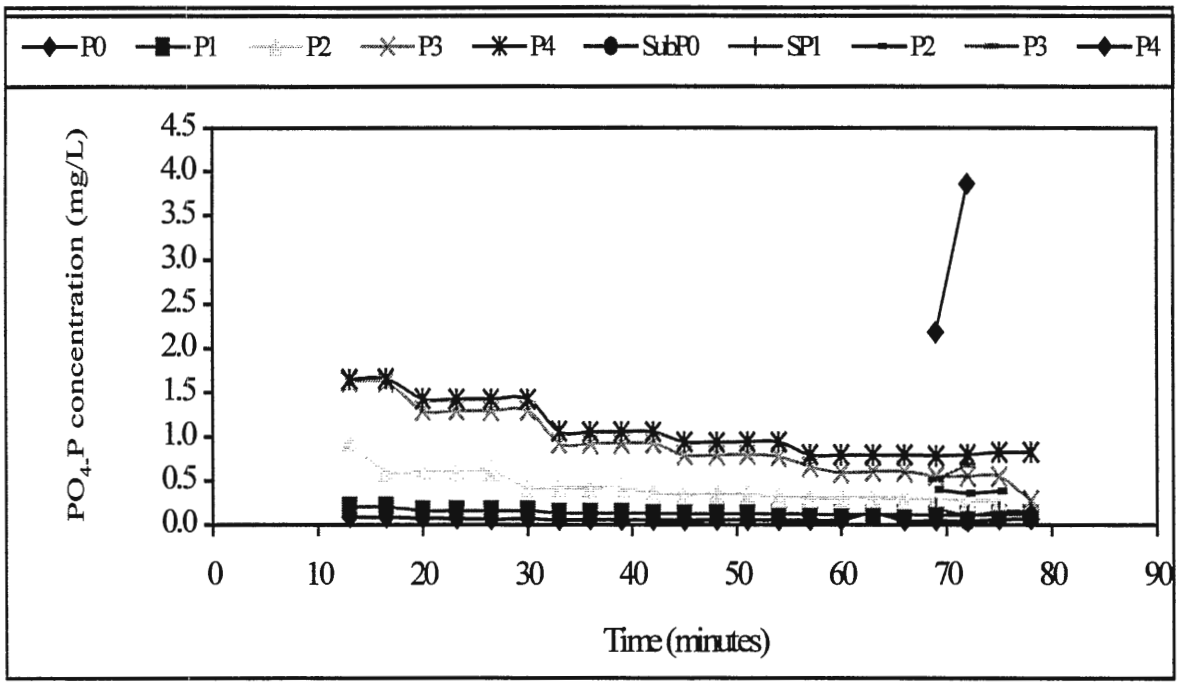

Figure 40. Average flow-weighted concentrations of PO_4-P phosphorus in runoff and subsurface drainage water from Marshall soil.

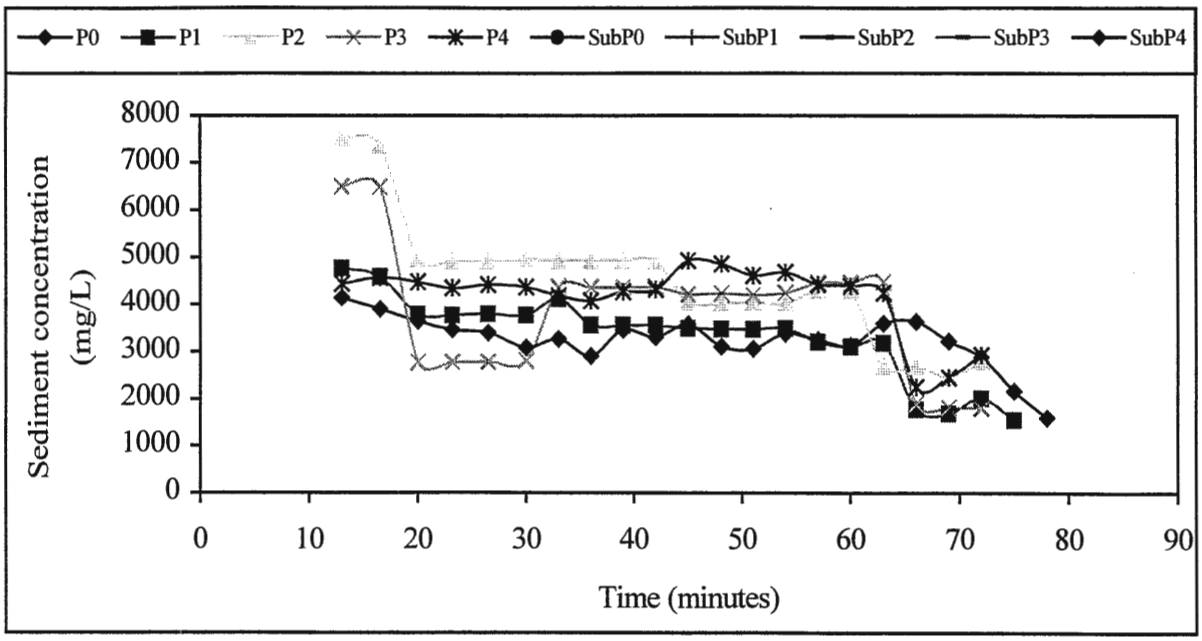

Figure 41. Average flow-weighted concentrations of sediment in runoff and subsurface drainage water from Marshall soil.

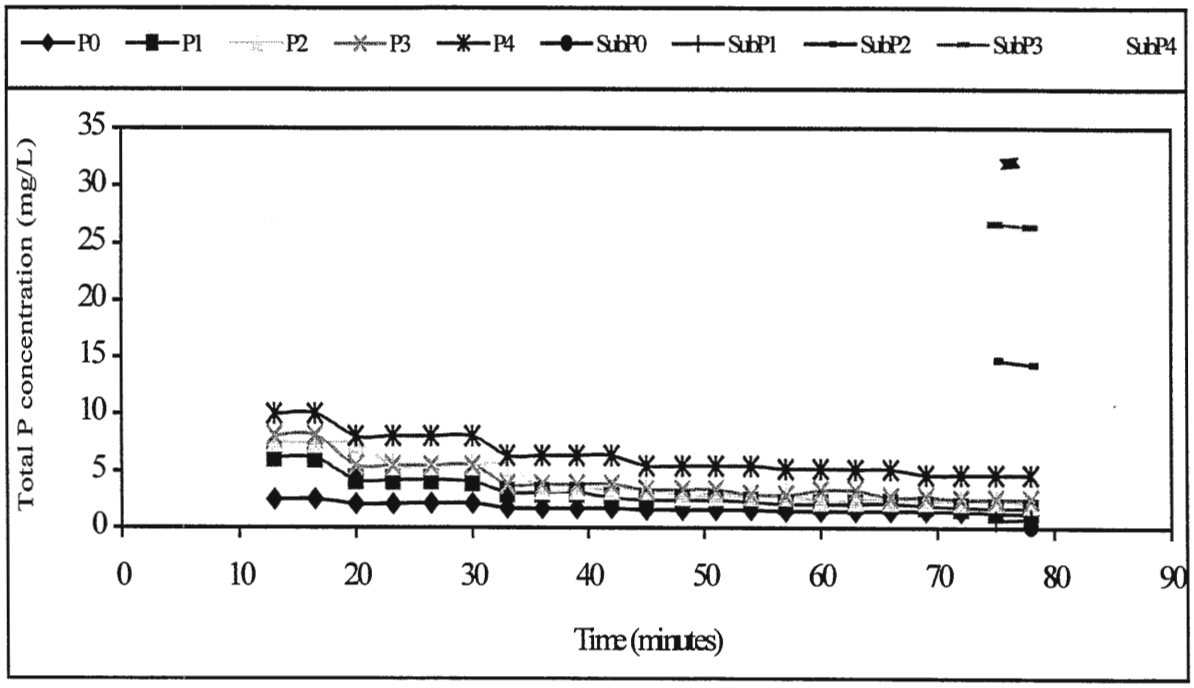

Figure 42. Average flow-weighted concentrations of total-P in runoff and subsurface drainage water from Marshall soil.

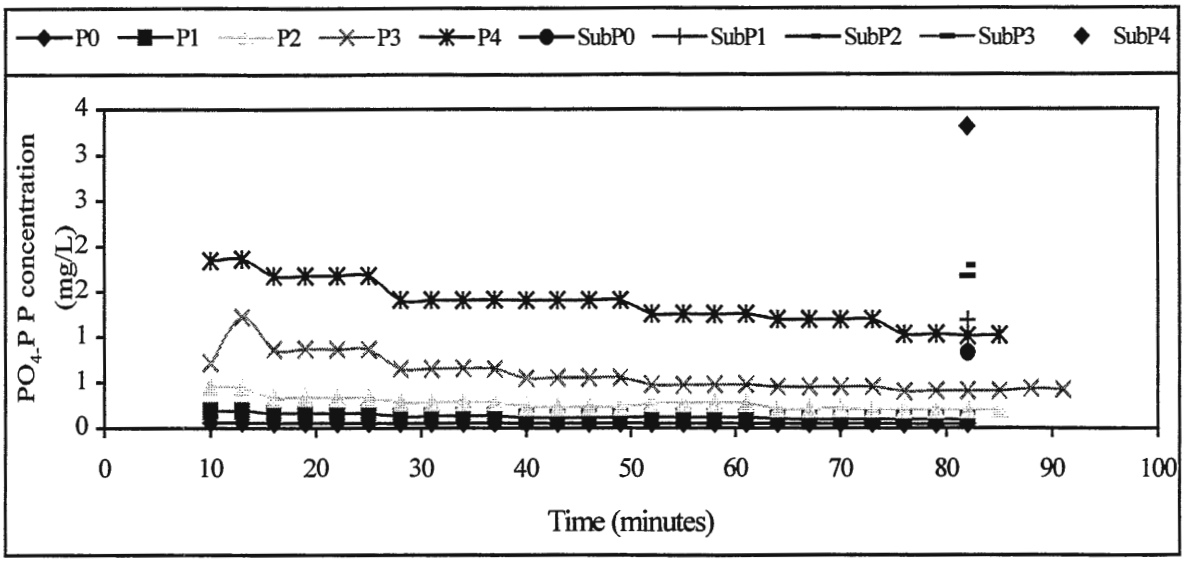

Figure 43. Average flow-weighted concentrations of PO_4-P in runoff and subsurface drainage water from Fayette soil.

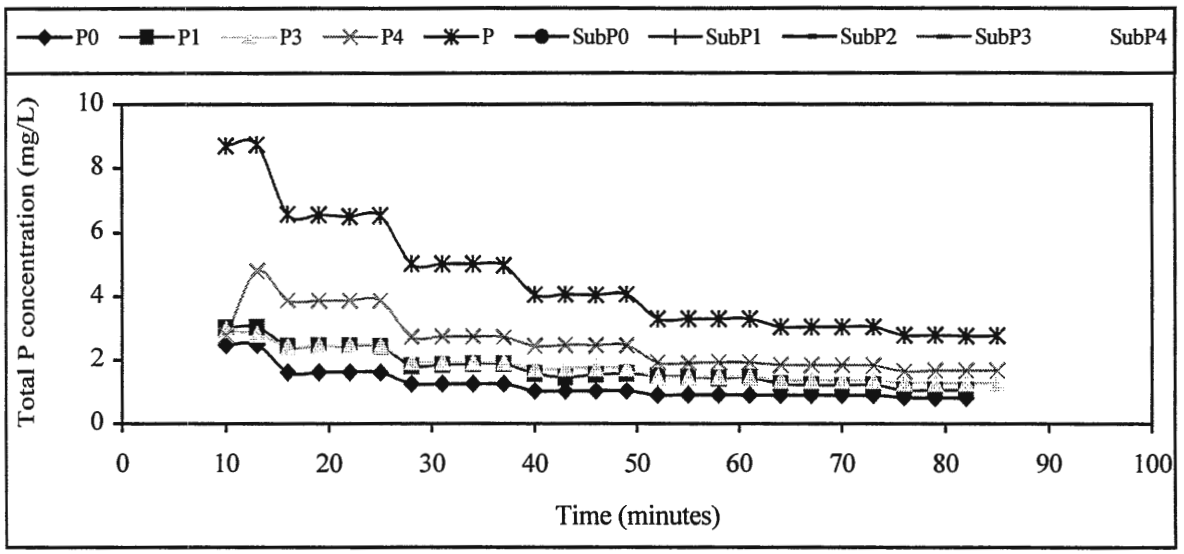

Figure 44. Average flow-weighted concentrations of total-P in runoff and subsurface drainage water from Fayette soil.

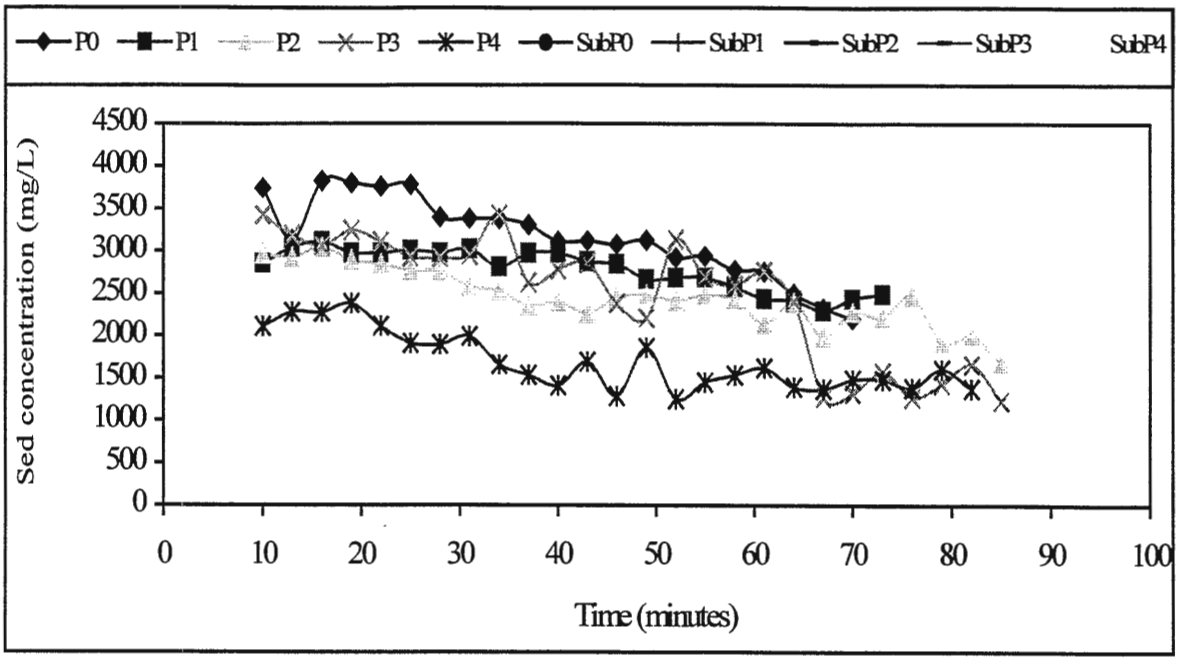

Figure 45. Average flow-weighted concentrations of sediments in runoff and subsurface drainage water from Fayette soil.

CHAPTER 5. CONCLUSIONS

The purpose of this study was to determine P concentrations and losses in surface runoff and subsurface drainage as affected by amount of P added to soils and rainfall energy. Emphasis was also placed on the relationships between the soil test P revels as measured by Bray P-1, PO_4-P, total-P, and sediment. Three soils representing a wide range in chemical and physical properties found in three principal soil associations in Iowa were included in this study.

In this new era, the world is facing an increasing concern of balancing crop production and protecting the environment. The objective of this study was to better understand factors that cause or contribute to P transport with sediment and water in surface runoff and subsurface drainage. This information could become part of the P-index by used to assist producers and agriculturalists in to developing a plan that efficiently utilize all sources of nutrients and at the same time maintains or increases agricultural profitability and a respect for the environment. Simulated rainfall was applied to two boxes at a time (with and without a screen cover) at the first phase of the research to determine the effect of P added to different Iowa soils (five levels using MAP) and the impact of rainfall energy.

The average concentrations for PO_4-P and total-P were significantly greater with the P_4 treatment which was equal to 600 ppm added P. The screen treatment did not result in large differences in P concentrations and for that reason, was not studied further. PO_4-P total-P, and sediment losses in surface runoff water were significantly greater without the cover than with it. Concentrations of P were significantly higher for subsurface drainage in comparison with surface runoff.

The soil test results, after 30 days of incubation showed a high correlation between added P and available P, ($r^2 = 0.989$ for Nicollet, $r^2 = 0.999$ for Marshall, and $r^2 = 0.982$ for Fayette). This study showed that high P concentrations in surface runoff from soils with very high soil test levels of P could cause losses of P at levels that seriously affect water quality and adversely affect the aquatic environment. Using the optimum test level for application of P should, therefore, be encouraged to minimize contamination of surface and groundwater contamination. Other management practices should also be considered, such as avoiding excess applications on steeply sloping terrain, maintaining buffers and riparian strips, and avoiding application on frozen or covered snow soils.

The results presented show the concentrations of P in surface runoff water were appreciably influenced by the levels of P added in soil and the impact of the rainfall energy on the soil surface. The experimental data obtained indicated the influence of above factors on the soil P release into runoff and show that the average runoff concentration from the Nicolett, Marshall, and Fayette soils as a function of time, in all cases was relatively similar. The relative effect of the non screen treatment versus the screen treatment, which was due to impact of raindrops on the bare soil, was more and quicker surface runoff and an accelerating of a sediment detachment from the boxes. The screen treatment decreased the P release from soil and decreased the concentrations of PO_4-P and total-P in surface runoff. The physical and chemical properties of the tree different soils samples showed wide variations, but there were no consistent relationships between the different soil characteristics and the initial or later levels of available P as measured by Bray P-1 test.

Results presented also gave some promise that the effect of added P on different soils, as newly developed information for environmental water quality control, can be used to help

estimate or predict the concentration losses of P and of P in surface runoff water. However, more information and data are needed to address more specific issues. There is increasing quality concern about the side effects of excessive manure or excessive fertilizer P application rates, which will increase soil P test levels, with consequences of potential P release either in surface runoff and or subsurface drainage water.

Added P had essentially the same availability for all three soils regardless of the differences in the soil pH, presence of $CaCO_3$, organic matter content, soil texture, initial levels of available soil P, or variations in other unmeasured soil characteristics. The percentage of added P that remained "available" decreased uniformly for all soils after 30 days of incubation. The Bray P-1 test, however, indicated a very rapid initial reduction in the amount of extracted P after the P fertilizer monobasic ammonium phosphate (MAP) was added to the soil. This might be expected to be followed by a slower but continued decrease in the amounts of P extracted with time of incubation; however, no measurements were made beyond that at 30days.

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